APPENDIX D
INLET CAPACITY AND SPACING

1.0 Introduction

The capacity and spacing design of storm drainage inlets are presented in detail in this Appendix.

2.0 Design Recurrence Interval and Spread

The hydraulic capacity of a storm drain inlet depends upon its geometry as well as the characteristics of the gutter flow. Inlet capacity governs both the rate of water removal from the gutter and the amount of water that can enter the storm drainage system. Inadequate inlet capacity or poor inlet location may cause flooding on the roadway resulting in a hazard to the traveling public.

The following table provides guidance of the appropriate design recurrence interval, allowable spread, and clogging factors based on road classification. These parameters should be used to design and/or analyze gutter flow and inlet capacity.

Table A - Pavement Drainage Design Parameters

Road Classification			Recurrence Interval (years)	Spread	Clogging (percent)
Highways, Freeways and Collectors	Less than 45 miles per hour	On-grade	10	Shoulder + 2 feet	30*
		Local sag point	25	Shoulder + 2 feet	50
		Main line sag point	50	Shoulder + 2 feet	50
	Greater than or equal to 45 miles per hour	On-grade	10	Shoulder	30*
		Local sag point	25	Shoulder	50
		Main line sag point	50	Shoulder	50
Local Streets and Frontage Roads		On-grade	10	1/2 Driving Lane or local standard	30*
		Local sag point	25	1/2 Driving Lane or local standard	50
		Main line sag point	50	1/2 Driving Lane or local standard	50

Note: Reference Section 13.3 for definitions of local and main line sag points.

** Always use a clogging factor of 50 percent for slotted drains, trench drains, and scuppers.*

Inlets on-grade shall meet the following criteria:

- Inlets on-grade shall be spaced for a 5-minute, 10-year rainfall intensity. Design on-grade inlets using Method A or Method B.
- The maximum gutter flow width shall be limited to the spread described in Table A.
- Spacing of first inlet from the crest shall be as calculated to meet spread widths.
- The maximum inlet spacing for subsequent inlets shall be limited to 400 feet.
- Section 5 provides additional design guidelines for inlets on-grade.

Inlets in sags shall meet the following criteria:

- Inlets in a sag shall be designed for a 5-minute, 25-year or 50-year rainfall intensity (reference Table A). Design inlets in a sag using Method A or Method B.
- The design discharge shall be the 25-year or 50-year bypass flow (reference Table A) from the first upstream inlet on each side of the sag plus the runoff from any additional areas draining to the sag.
- One inlet shall be placed at the lowest point in the sag. Flanking inlets shall be included in sag locations. One flanking inlet shall be placed on each side of the low point inlet. Additional flanking inlet design guidelines are discussed in Section 6.6.
- Section 6.0 provides additional design guidelines for inlets in sags.

Note: There are two methods for designing stormwater inlets. These methods are discussed in more detail below. The key difference between the two methods is that Method A assumes a grate operates in an unclogged condition and no more than 30 percent of the flow would bypass during the design event identified in Table A. Method B has no established minimum inlet efficiency, however, the inlet is assumed 30 to 50 percent clogged as noted in Table A.

METHOD A:

- The bypass flow for inlets on grade shall be limited to a maximum of 30 percent.
- No clogging factors need be used (assume zero percent clogging).
- Low point inlets shall be designed using the allowable spread width from Table A.

METHOD B:

- The bypass flow for on-grade inlets may be maximized to use the entire allowable spread width from Table A.
- Clogging factors as described in Table A (as a minimum) and Section 4.0 shall be used.

3.0 Inlet Spacing and Computation Sheets

Inlet spacing design consists of locating the inlet, calculating the peak runoff (hydrology), determining the spread, and evaluating inlet efficiency. This design process can be viewed as a circular process that does not have a defined starting point and order of the process can vary as described in this section.

The design starting point depends on site drainage characteristics. For example, some inlets are placed to collect runoff at locations with little regard for contributing area such as immediately up grade from pedestrian cross walks, entrance/exit ramp gores, sags, etc. Based on diagram A-A, the design process would begin at *Locate Inlet*, proceed to *Calculate Hydrology*, leading to spread calculations and end with calculating inlet efficiency. Additional detail on this design process is presented in this section.

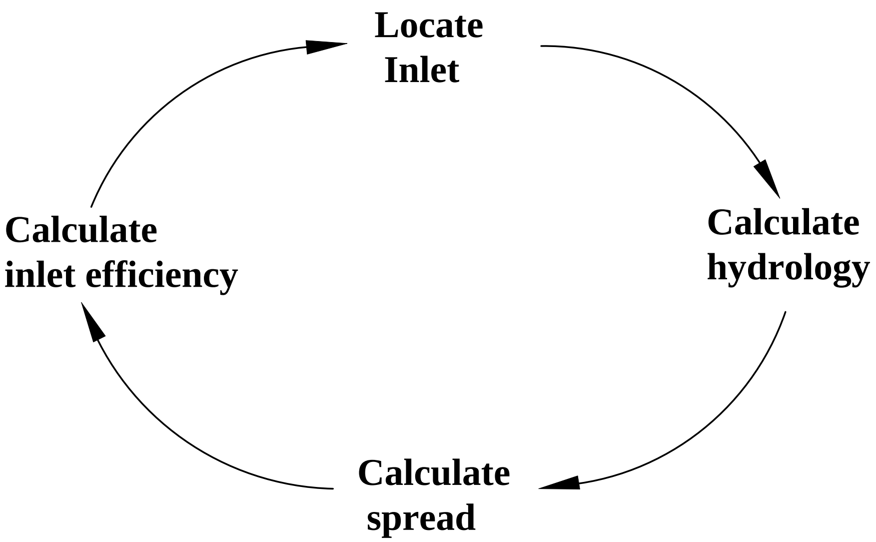

Diagram A - A

Note: Figure 1 is a computation summary sheet that is recommended to document the analysis process noted in Diagram A-A.

Inlet spacing design could also begin by the designer assuming a spread width. This is a common approach to evaluating inlets placed on continuous grades. Based on diagram B-B, the design process would begin at *assume spread*, then compute hydrology, inlet efficiency, and end with calculating inlet spacing.

Note: Figure 2 is a computation summary sheet that is recommended to document the analysis process noted in Diagram B-B.

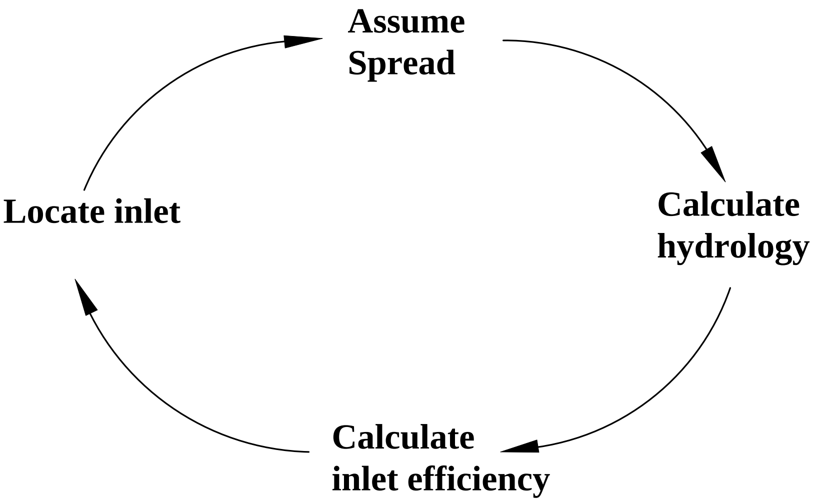

Diagram B - B

Geometric information is needed when designing storm drainage inlets. The type of information needed for design includes highway longitudinal slope, cross slope, gutter characteristics, location of crest and sag points, drainage patterns, and delineated drainage areas. This information can be obtained from highway profiles, typical cross sections, superelevation diagrams, and surveyed maps with contours.

A number of inlets are required to collect runoff at locations with little regard for contributing drainage area. Locate and note these inlets on the design plan. After locating these inlets, obtain and use the roadway geometric information to assure that the design criteria such as minimum inlet efficiency and maximum gutter flow widths are not exceeded. If the design criteria are not satisfied, adjustments to the inlet system (e.g. type of inlet, inlet spacing, etc) may be required. This information should be included on the computation sheet (Figure 1) provided to document the analysis.

The spacing of inlets on continuous grades is based on the maximum spread allowed per Table A. Two methods (A or B) are available for designing these types of inlets and are defined in Section 2. The first inlet and subsequent inlets are placed downstream of the crest point to meet the requirements of methods A or B. These inlets can be equally spaced when the drainage areas consists of pavement only, uniform runoff characteristics, and are rectangular in shape. It is also assumed that the time of concentration would be the same for all inlets.

The following equation can be used to locate the first on-grade inlet on continuous grade: (subsequent inlets have a 400 foot maximum spacing)

$$L = 43560 \frac{Q_t}{CC_f iW_p} E \qquad \text{(Equation 1)}$$

Where:

L = distance from the crest in feet

W_p = width of drainage area in feet

C = runoff coefficient

C_f = runoff coefficient adjustment factor to account for reduction of infiltration and other losses during high intensity storms (See **Chapter 7**, Appendix F; for 10-year storm $C_f = 1$)

i = rainfall intensity in inches per hour

Q_t = maximum allowable flow in cubic feet per second (calculated as noted in Section 13.7 and **Chapter 7**).

E = This constant is equal to one for the first inlet in all cases and is equal to capture efficiency (E) for subsequent inlets. The constant E can be assumed to be equal to 1 for the first inlet because it receives almost no bypass flow from upslope inlets. To space successive down grade inlets on constant slope, use the capture efficiency (E).

43,560 = conversion from acres to square feet

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Inlet Design Computation Sheet (Diagram A-A Process)

Given:

Surface Description	
Road Classification	
Type of Curb and Gutter, see Chapter 8, Curbs and Gutters	
Surface Material	
Manning's Coefficient, n	
Drainage Area Description	
Runoff Coefficient, C	
Hydrologic Zone *(Chapter 7)*	
Intensity (i) in/hr *(Chapter 7)*	
C_f *(Chapter 7, Appendix F)*	
Type of Inlet *(Chapter 13, Appendix C, Table B)*	
Design Method: **Method A** ☐ **Method B** ☐	
Design Criteria:	
Method A (reference Section 2)	
Minimum Efficiency	70 Percent
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	
Method B (reference Section 2)	
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	

Sketch:

Locate Inlet			Calculate Hydrology			Calculate Spread								Calculate Inlet Efficiency					
Drainage Length	Drainage Width	Drainage Area	Flow from Contributing Area	Bypass Flow from Upstream Inlet	Total Flow	Spread	Long. Slope	Cross Slope		Gutter Width	Total Gutter Flow	Design Inlet Length	Design Inlet Width	Inlet Interception Efficiency	Intercepted Flow	Bypass Flow	Number	Station	Comments
L (ft)	W_p (ft)	A (ac)	Q_r (cfs)	Q_b (cfs)	Q_t (cfs)	T (ft)	S_L (ft/ft)	S_x (ft/ft)	S_w (ft/ft)	W (ft)	Q_t (cfs)	L_i (ft)	W_i (ft)	E	Q_i (cfs)	Q_b (cfs)			

Figure 1 – Computation Sheet For Inlet Design

Inlet Design Computation Sheet (Diagram B-B Process)

Given:

Surface Description	
Road Classification	
Type of Curb and Gutter, see Chapter 8, Curbs and Gutters	
Surface Material	
Manning's Coefficient, n	
Drainage Area Description	
Runoff Coefficient, C	
Hydrologic Zone *(Chapter 7)*	
Intensity (i) in/hr *(Chapter 7)*	
C_f *(Chapter 7, Appendix F)*	
Type of Inlet *(Chapter 13, Appendix C, Table B)*	
Design Method: Method A ☐ Method B ☐	
Design Criteria:	
Method A (reference Section 2)	
Minimum Efficiency	70 Percent
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	
Method B (reference Section 2)	
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	

Sketch:

Assume Spread								Calculate Hydrology			Calculate Inlet Efficiency			Locate Inlet					
Spread	Long. Slope	Cross Slope		Gutter Width	Total Gutter Flow	Design Inlet Length	Design Inlet Width	Flow from Contributing Area	Bypass Flow from Upstream Inlet	Total Flow	Inlet Interception Efficiency	Intercepted Flow	Bypass Flow	Drainage Length	Drainage Width	Drainage Area	Number	Station	Comments
T	S_L	S_x	S_w	W	Q_t	L_i	W_i	Q_r	Q_b	Q_t	E	Q_i	Q_b	L	W_p	A			
(ft)	(ft/ft)	(ft/ft)	(ft/ft)	(ft)	(cfs)	(ft)	(ft)	(cfs)	(cfs)	(cfs)		(cfs)	(cfs)	(ft)	(ft)	(ac)			

Figure 2 – Computation Sheet for Inlet Design

4.0 Clogging Factors

Refer to Table A for on-grade and sag inlet clogging factors. Table A provides guidance on the clogging factor recommended based on road classification. Then go to the appropriate ODOT inlet design parameter clogging tables (Table B for 30 percent clogged or Table C for 50 percent clogged) for grate, curb-opening or slot width and length to be used for designing inlets partially clogged. Hydraulic capacity curves or data for available grates would have to be obtained from a manufacturer when evaluating trench drains.

Assume 50 percent clogging for the following inlet types when using inlet design method B due to the tendency of these inlets to plug:

- Slotted drains
- Trench drains
- Scuppers

Using a 50 percent clogging factor will result in providing twice the calculated required length than if no clogging factor were used.

Note: Some assumptions must be made regarding the nature of the clogging in order to compute the capacity of a partially clogged grate. If the area of a grate is 50 percent covered by debris so that the debris-covered portion does not contribute to interception, the effective perimeter will be reduced by a lesser amount than 50 percent.

4.1 Grate Clogging Calculation Example

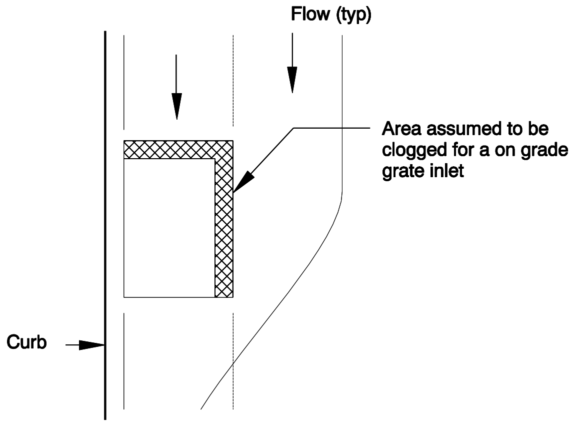
The following example illustrates the application of clogging factors.

4.1.1 Grate configuration assuming 50 percent clogged

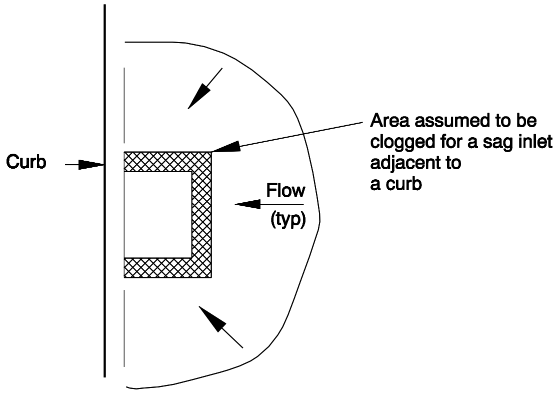
Tables B and C in this appendix identify adjusted widths to account for 30 percent and 50 percent clogging as required for Method B. The following is included to illustrate how inlet dimensions are adjusted to account for clogging. Reference Figure 3 of this Appendix to gain a conceptual understanding of the clogged inlets.

If a 24-inch by 48-inch grate is located next to a curb at a sag and is assumed to be 50 percent clogged. The effective width is 12-inches, reduced from 24-inches to 12-inches. Likewise, the perimeter is reduced from 96-inches to 72-inches (12-inches + 48-inches + 12-inches). The area of the opening would be reduced by 50 percent and the perimeter by 25 percent. To provide an equivalent interception capacity of a grate with a perimeter of 96-inches several alternatives may be available. These alternatives include a grate measuring 48-inches by 48-inches, a grate measuring 24-inches by 72-inches, or a grate measuring 36-inches by 60-inches would meet these requirements.

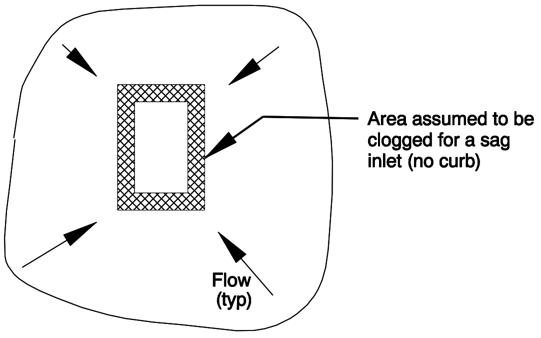
Note: Figure 3 illustrates typical inlet grate areas assumed to be clogged if placed on-grade, sag with curb or sag with no curb.



a) On grade



b) Sag with curb



c) Sag no curb

Figure 3 - Grate Clogging

Table B - ODOT Inlet Design Parameters with 30 Percent Clogging

Identification	Next to Curb	Grate, curb-opening or slot Width (feet)	Grate, curb-opening or slot Length (feet)	Grate Perimeter (feet)	Clear Opening	
					Area (square feet)	Ratio (percent)
G-1 & CG-1	Y	1.39	2.31	5.10	2.41	75
G-1	N	1.39	2.31	7.41	2.41	75
G-2 & CG-2	Y	1.84	2.26	5.94	2.99	72
G-2	N	1.84	2.26	8.20	2.99	72
G-2M & G-2MA	N	1.84	2.26	8.20	3.33	80
CG-3	Y	h = 0.36	1.75	N/A	0.63	N/A
Curb Inlet Channel	Y	h = 0.33	4.20	N/A	1.39	N/A
D	N	1.58	h = 1.38	N/A	1.74	80
Type 3 Catch Basin	Y	1.89	1.89	5.68	1.43	40
Type 3 Catch Basin	N	1.89	1.89	7.57	1.43	40
Area Drainage Basin or Field Inlet (Round)	N	1.65	1.65	5.18	1.45	68
Slotted Drain	Y/N	0.15	70 percent of length shown on plans	N/A	N/A	N/A
Deck Drain Type A	Y	0.86	2.40	4.12	1.16	56

Table C - ODOT Inlet Design Parameters with 50 Percent Clogging

Identification	Next To Curb	Grate, curb-opening or slot Width (feet)	Grate, curb-opening or slot Length (feet)	Grate Perimeter (feet)	Clear Opening	
					Area (square feet)	Ratio (percent)
G-1 & CG-1	Y	1.13	2.05	4.31	1.74	75
G-1	N	1.13	2.05	6.36	1.74	75
G-2 & CG-2	Y	1.53	1.95	5.00	2.15	72
G-2	N	1.53	1.95	6.96	2.15	72
G-2M & G-2MA	N	1.53	1.95	6.96	2.39	80
CG-3	Y	h = 0.36	1.25	N/A	0.45	N/A
Curb Inlet Channel	Y	h = 0.33	3.00	N/A	0.99	N/A
D	N	1.12	h = 1.38	N/A	1.24	80
Type 3 Catch Basin	Y	1.60	1.60	4.80	1.02	40
Type 3 Catch Basin	N	1.60	1.60	6.40	1.02	40
Area Drainage Basin or Field Inlet (Round)	N	1.39	1.39	4.38	1.03	68
Slotted Drain	Y/N	0.15	50 percent of length shown on plans	N/A	N/A	N/A
Deck Drain Type A	Y	0.67	2.21	3.56	0.83	56

5.0 Inlets on Grade

Inlet interception capacity (Q_i) is the flow intercepted by an inlet under a given set of conditions. The efficiency (E) of an inlet is the percent of total flow that the inlet will intercept for those conditions. The efficiency of an inlet is dependent on the cross slope, longitudinal slope, total gutter flow, and pavement roughness. Efficiency is defined by the following equation:

$$E = \frac{Q_i}{Q_t} \qquad \text{(Equation 2)}$$

Where:

E = inlet efficiency

Q_t = total gutter flow in cubic feet per second

Q_i = intercepted flow in cubic feet per second

Flow that is not intercepted by an inlet is termed carryover or bypass flow and is defined as follows:

$$Q_b = Q_t - Q_i \qquad \text{(Equation 3)}$$

Where:

Q_b = flow that is not intercepted by the inlet and must be included in the evaluation of downstream gutters, channels, and inlets

The interception capacity of all inlet configurations increases with increasing flow rates, and inlet efficiency generally decreases with increasing flow rates. Factors affecting gutter flow also affect inlet interception capacity. The depth of water next to the curb is the major factor in the interception capacity of both grate inlets and curb-opening inlets. The interception capacity of a grate inlet depends on the amount of water flowing over the grate, the size and configuration of the grate and the velocity of flow in the gutter.

Interception capacity of a curb-opening inlet is largely dependent on flow depth at the curb and curb-opening length. Flow depth at the curb and consequently, curb-opening inlet interception capacity and efficiency, is increased by the use of a local gutter depression at the curb-opening or a continuously depressed gutter to increase the proportion of the total flow adjacent to the curb.

Slotted drain inlets function in essentially the same manner as curb-opening inlets, i.e., as weirs with flow entering from the side. Interception capacity is dependent on flow depth and inlet length. Efficiency is dependent on flow depth, inlet length and total gutter flow.

The interception capacity of an equal length combination inlet consisting of a grate placed alongside a curb-opening on a grade does not differ materially from that of a grate only. Interception capacity and efficiency are dependent on the same factors which affect grate capacity and efficiency. A combination inlet consisting of a curb-opening inlet placed upstream of a grate inlet has a capacity equal to that of the curb-opening length upstream of the grate plus that of the grate, taking into account the reduced spread and depth of flow over the grate because of the interception by the curb-opening. This inlet configuration has the added advantage of intercepting debris that might otherwise clog the grate and deflect water away from the inlet.

5.1 Grate Inlets (On-grade)

The capacity of a grate inlet depends upon its geometry, cross slope, longitudinal slope, total gutter flow, depth of flow and pavement roughness. The depth of water next to the curb is the major factor in the interception capacity of gutter inlets. At low velocities, all of the water flowing in the section of gutter occupied by the grate, called frontal flow, is intercepted by grate inlets, and a small portion of the flow along the length of the grate, termed side flow, is intercepted. On steep slopes, a portion of the frontal flow may tend to splash over the end of the grate for some grates. Chart 1 in Appendix H can be utilized to determine splash-over velocities (V_o) for various grate configurations and the portion of frontal flow intercepted by the grate.

Note:

- *Standard grate inlets used in ODOT storm drainage systems are noted in Appendix C.*
- *The parallel bar grates are the most efficient grates on steep slopes but are not bicycle safe.*

The ratio of frontal flow to total gutter flow (E_o) for straight cross slope is expressed by the following equation:

$$E_o = \frac{Q_w}{Q_t} = 1 - \left(1 - \frac{W}{T}\right)^{2.67} \qquad \text{(Equation 4)}$$

Where:

Q_t = total gutter flow in cubic feet per second
Q_w = flow in width (W) in cubic feet per second
W = width of depressed gutter or grate in feet
T = total spread of water in the gutter in feet

Chart 2 in Appendix H provides a graphical solution of (E_o) for either straight cross slopes or depressed gutter sections.

The ratio of side flow (Q_s) to total gutter flow is:

$$\frac{Q_s}{Q_t} = \frac{1 - Q_w}{Q_t} = 1 - E_o \qquad \text{(Equation 5)}$$

The ratio of frontal flow intercepted to total frontal flow (R_f) is expressed by the following equation:

$$R_f = 1 - 0.09\,(V - V_o) \qquad \text{(Equation 6)}$$

Where:

V = velocity of flow in the gutter in feet per second
V_o = gutter velocity where splash-over first occurs in feet per second

Note: R_f can not exceed 1.0. If V is less than V_o, R_f =1, meaning that all flow is intercepted. If V is greater than V_o, R_f is less than 1, meaning that a portion of frontal flow is intercepted.

This ratio is equivalent to frontal flow interception efficiency. Chart 1 in Appendix H provides a solution of which takes into account grate length, bar configuration and gutter velocity at which splash-over occurs. The gutter velocity needed to use Chart 1 in Appendix H is total gutter flow divided by the area of flow.

Note: Chart 3 in Appendix H is a Nomograph to solve for velocity in a triangular gutter section with known cross slope, slope and spread. Additional nomographs are located in Chapter 8.

The ratio of side flow intercepted to total side flow (R_s) or side flow interception efficiency, is expressed by:

$$R_s = \frac{1}{1+\left(\frac{0.15\,V^{1.8}}{S_x L^{2.3}}\right)} \qquad \text{(Equation 7)}$$

Where:

V = velocity of flow in gutter in feet per second
L = length of the grate in feet
S_x = cross slope in foot per foot

Chart 4 in Appendix H provides a solution to Equation 7.

The efficiency (E) of a grate is expressed as:

$$E = R_f E_o + R_s(1 - E_o) \qquad \text{(Equation 8)}$$

The interception capacity (Q_i) of a grate inlet on grade is equal to the efficiency of the grate multiplied by the total gutter flow:

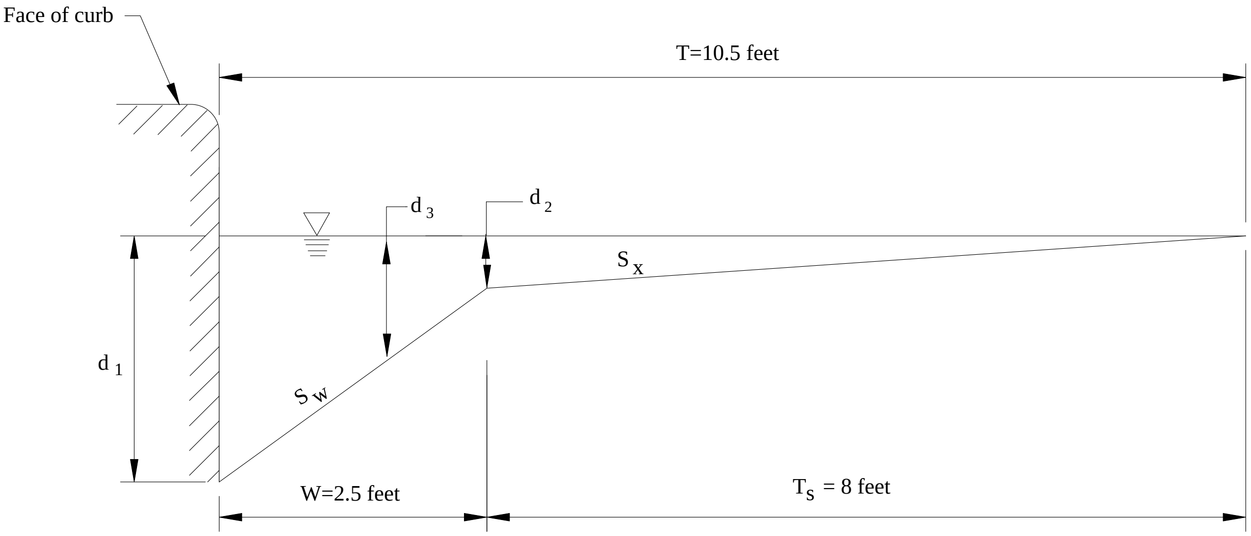
$$Q_i = E\,Q = Q\,[\,R_f E_o + R_s\,(1 - E_o)\,] \qquad \text{(Equation 9)}$$

5.1.1 Grate Inlet Capacity (On-grade) Example

The following example illustrates the application of inlet spacing, efficiency and by-pass equations.

5.1.1.1 Determine maximum allowable flow, interception flow, bypass flow, location of first inlet, and spacing of subsequent inlets.

Sketch:



Given:

- Highway on-grade section (greater than or equal to 45 miles per hour)
- Curb and Gutter (reference **Chapter 8**)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- n = 0.014 (Manning's coefficient for concrete gutter w/ AC)
- S_x = 0.02 foot per foot (shoulder and roadway cross slope)
- S_L = 0.035 foot per foot (roadway longitudinal slope)
- W_p = 46.5 feet (width of contributing drainage area, 2 – 12-foot lanes with 10.5 foot shoulder/gutter, 5 foot sidewalk, 7 foot median)
- W = 2.5 feet (gutter width)
- S_w = 0.05 foot per foot (gutter slope)
- C = 0.90 (rational method runoff coefficient for pavement)
- 10-year design, Hydrologic Zone 8 (IDR curves are located in **Chapter 7**)
- G-2 inlet with P-1 $^7/_8$ – 4 grate (reference Table B, Appendix C)
- W_g = 2.25 feet (grate width for G-2 grate inlet)
- L_g = 2.67 feet (grate length for G-2 grate inlet)

5.1.1.2 Method A

Criteria:

- Allowable spread is 0 feet into the outside lane (reference Table A, Appendix D)
- Therefore; T = allowable spread
  = shoulder width + gutter width
  = 8 feet + 2.5 feet = 10.5 feet
- E = 0.70 (minimum efficiency for Method A)
- L_2 = 400 feet (maximum distance between successive inlets, reference Section 2, Appendix D)

Solution:

Step A.1- Solve for (d_1, d_2, d_3):

d_1 = flow depth at curb = (T-W) S_x + WS_w
d_2 = flow depth at break in gutter cross slope = (T-W) S_x (Chapter 8)
d_3 = flow depth at edge of inlet = (T-W) S_x + (W-grate width) S_w

d_1 = (10.5 – 2.5)(0.02) + (2.5)(0.05) = 0.285 feet
d_2 = (10.5 – 2.5)(0.02) = 0.16 feet
d_3 = (10.5 – 2.5) (0.02) + (2.5 – 2.25)(0.05) = 0.1725 feet

Step A.2- Solve for (Q_t):

Q_t = total gutter flow (cubic feet per second)

$$Q_t = \frac{0.56\,S_L^{0.5}\,d_2^{2.67}}{n\,S_x} + \frac{0.56\,S_L^{0.5}\,(d_1^{2.67} - d_2^{2.67})}{n\,S_w} \qquad \begin{bmatrix}\text{Chapter 8 or Chart 2}\\ \text{and 5, Appendix H}\end{bmatrix}$$

$$Q_t = \frac{0.56\,(0.035)^{0.5}\,(0.16)^{2.67}}{(0.016)(0.02)} + \frac{0.56\;(0.035)^{0.5}\,(0.285^{2.67} - 0.16^{2.67})}{(0.014)(0.05)}$$

Q_t = 2.46 + 4.25 = 6.71 cubic feet per second

Step A.3- Solve for (Q_w):

Q_w = flow in width (W) or frontal flow, equal to the grate width (in cubic feet per second)

$$Q_w = \frac{0.56\,S_L^{0.5}\,(d_1^{2.67} - d_3^{2.67})}{n\,S_w}$$

(**Chapter 8** or Chart 5, in Appendix H)

$$= \frac{0.56(0.035)^{0.5}(0.285^{2.67} - 0.1725^{2.67})}{(0.014)(0.05)}$$

Q_w = 3.87 cubic feet per second

Step A.4- Solve for (V):

V = average gutter flow velocity (in feet per second)

$$V = \frac{Q_t}{A} = \frac{2Q_t}{T_s^2 S_x + W^2 S_w + 2WT_s S_x} = \frac{2Q_t}{\left[W(d_1 + d_2) + \frac{d_2^2}{S_x}\right]} \qquad \textbf{(Chapter 8)}$$

$$V = \frac{2\,(6.71)}{(8)^2(0.02) + (2.5)^2(0.05) + (2)(2.5)(8)(0.02)} = 5.61 \text{ feet per second}$$

Step A.5- Solve for (E_o):

E_o = the ratio of frontal flow to total gutter flow

$$E_o = \frac{Q_w}{Q_t} = \frac{3.87}{6.71} = 0.577 \qquad \text{(Equation 4 or Chart 2 in Appendix H)}$$

Step A.6- Solve for (R_f):

R_f = the ratio of frontal flow intercepted to total frontal flow

R_f = 1 – 0.09 (V – V_o) (Equation 6 or Chart 1 in Appendix H)

Where:
V = average flow velocity in the gutter (in feet per second)
V_o = gutter velocity where splash over first occurs (in feet per second)
V = 5.61 feet per second

G-2 Grate length = 2.67 feet
Grate type = P – $1^7/_8$ – 4
V_o = 5.9 feet per second (per Chart 1, Appendix H)

R_f = 1 – 0.09 (5.61 – 5.9)
R_f = 0.97
R_f cannot exceed 1.0, therefore,
R_f = 0.97

Step A.7- Solve for (R_s):

R_s = the ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1 + \left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)} \qquad \text{(Equation 7 or Chart 4, Appendix H)}$$

$$R_s = \frac{1}{1+\left(\frac{0.15\,(5.61)^{1.8}}{(0.02)(2.67)^{2.3}}\right)}$$

$$R_s = 0.054$$

Step A.8- Solve for (E):

E = the inlet interception efficiency

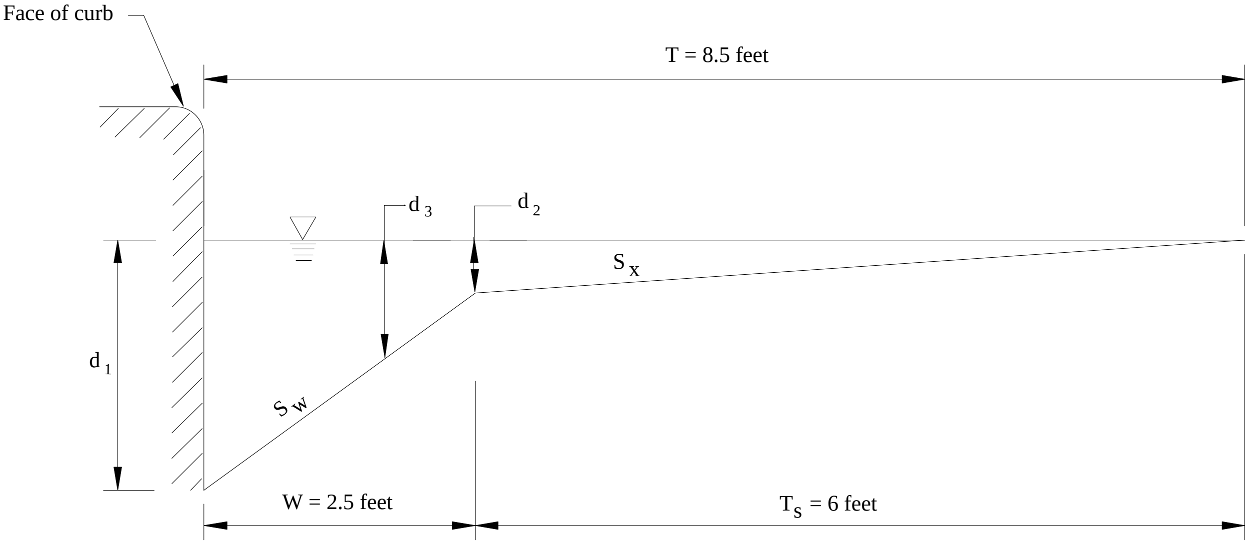
$$E = R_f E_o + R_s (1 - E_o) \qquad \text{(Equation 8)}$$

$$E = (1.0)(0.56) + .054 (1 - 0.56) = 0.58$$

E is less than 0.70, therefore, more than 30 percent would bypass inlet. A narrower flow width (T) would be assumed and steps 1 through 8 would be repeated until the minimum efficiency of 0.70 is obtained.

Try T = allowable spread = 8.5 feet

Sketch:



Step A1.2- Solve for (d_1, d_2, d_3):

d_1 = flow depth at curb = (T-W) S_x + WS_w
d_2 = flow depth at break in gutter cross slope = (T-W) S_x (**Chapter 8**)
d_3 = flow depth at edge of inlet = (T-W) S_x + (W-grate width) S_w

d_1 = (8.5 – 2.5)(0.02) + (2.5)(0.05) = 0.245 feet
d_2 = (8.5 – 2.5)(0.02) = 0.12 feet
d_3 = (8.5 – 2.5) (0.02) + (2.5 – 2.25)(0.05) = 0.13 feet

Step A2.2- Solve for (Q_t):

Q_t = total gutter flow (cubic feet per second)

$$Q_t = \frac{0.56\, S_L^{0.5}\, d_2^{2.67}}{n\, S_x} + \frac{0.56\, S_L^{0.5}\, (d_1^{2.67} - d_2^{2.67})}{n\, S_w}$$ $\left[\begin{array}{c}\text{Chapter 8 or Chart 2} \\ \text{and 5, Appendix H}\end{array}\right]$

$$Q_t = \frac{0.56\,(0.035)^{0.5}\,(0.12)^{2.67}}{(0.016)(0.02)} + \frac{0.56\;(0.035)^{0.5}\,(0.245^{2.67} - 0.12^{2.67})}{(0.014)(0.05)}$$

Q_t = 1.14 + 2.98 = 4.12 cubic feet per second

Step A3.2- Solve for (Q_w):

Q_w = flow in width (W) or frontal flow, equal to the grate width (in cubic feet per second)

$$Q_w = \frac{0.56\, S_L^{0.5}\, (d_1^{2.67} - d_3^{2.67})}{n\;\, S_w}$$ (**Chapter 8** or Chart 5, Appendix H)

$$= \frac{0.56(.035)^{0.5}(0.245^{2.67} - 0.13^{2.67})}{(0.014)(0.05)}$$

Q_w = 2.86 cubic feet per second

Step A4.2- Solve for (V):

V = average gutter flow velocity (in feet per second)

$$V = \frac{Q_t}{A} = \frac{2Q_t}{T_s^2 S_x + W^2 S_w + 2WT_s S_x} = \frac{2Q_t}{\left[W(d_1 + d_2) + \frac{d_2^2}{S_x}\right]}$$ (**Chapter 8**)

$$V = \frac{2\,(4.12)}{(6)^2(0.02) + (2.5)^2(0.05) + (2)(2.5)(6)(0.02)} = 5.05 \text{ feet per second}$$

Step A5.2- Solve for (E_o):

E_o = the ratio of frontal flow to total gutter flow

$$E_o = \frac{Q_w}{Q_t} = \frac{2.86}{4.12} = 0.69$$ (Equation 4 or Chart 2, Appendix H)

Step A6.2- Solve for (R_f):

R_f = the ratio of frontal flow intercepted to total frontal flow

R_f = $1 - 0.09\,(V - V_o)$ (Equation 6 or Chart 1, Appendix H)

Where:
V = average flow velocity in the gutter (in feet per second)
V_o = gutter velocity where splash over first occurs (in feet per second)
V = 5.05 feet per second

G-2 Grate length = 2.67 feet
Grate type = $P - 1^7/_8 - 4$
V_o = 5.9 feet per second (per Chart 1, Appendix H)

R_f = $1 - .09\,(5.05 - 5.9)$
R_f = 0.92
R_f can not exceed 1.0, therefore,
R_f = 0.92

Step A7.2- Solve for (R_s):

R_s = the ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)}$$ (Equation 7 or Chart 4, Appendix H)

$$= \frac{1}{1+\left(\frac{0.15\,(5.05)^{1.8}}{(0.02)(2.67)^{2.3}}\right)}$$

R_s = 0.065

Step A8.2- Solve for (E):

E = the inlet interception efficiency

$E = R_f E_o + R_s\,(1 - E_o)$ (Equation 8)

E = (1.0)(0.67) + (0.065) (1 - 0.67)

E = 0.69 Okay

Step A9.2- Solve for (L_1):

L_1 = first inlet from the crest

$$L_1 = \frac{43{,}560\,Q_t}{C\,C_f\,i\,W_p}\,E$$ (Equation 1)

i = 2.28 inches per hour (Assume 5 minute t_c using a 10-year storm design, Hydrologic Zone 8, use IDR curve in **Chapter 7**)
C = 0.90
C_f = 1.0 (per Appendix F, **Chapter 7**)
W_p = 24 feet (2 – 12 foot lanes) + 8 foot shoulder + 2.5 gutter + 5 foot sidewalk + 7 foot median = 46.5 feet (width of contributing drainage area)
E = 1.0

$$L_1 = \frac{43560\,(4.12)}{(0.90)(1.0)(2.28)(46.5)}(1.0) = 1{,}881\,\text{feet}$$

Step A10.2- Solve for (L_2):

L_2 = distance to successive inlets

$$L_2 = \frac{43{,}560\,Q_i}{C\,C_f\,i\,W_p} \qquad \text{(Equation 1)}$$

Q_i = intercepted flow (in cubic feet per second)
Q_i = EQ_t = (0.70) (4.12) = 2.88 cubic feet per second

$$L_2 = \frac{43{,}560\,(2.88)}{(0.9)(1.0)(2.28)(46.5)} = 1{,}315\,\text{feet}$$

Maximum L_2 = 400 feet (per Appendix D)
Therefore, L_1 = 1,881 feet and L_2 = 400 feet

5.1.1.3 Method B

- Assume T = allowable spread
  = shoulder width + gutter width
  = 8 + 2.5 = 10.5 feet (per Table A for highway on-grade section; greater than or equal to 45 miles per hour)
- Assume 30 percent clogged (per Table A).
- L_g = 2.26 feet (grate length for G-2 grate inlet, 30 percent clogged, Table B)
- W_g = 1.84 feet (grate width for G-2 grate inlet, 30 percent clogged, Table B)
- L_2 = 400 feet, maximum distance to successive inlets (reference Appendix D)

Solution:

Step B.1- Solve for (d_1, d_2, d_3):

d_1 = flow depth at curb = $(T-W)S_x + WS_w$ (**Chapter 8**)
d_2 = flow depth at break in gutter cross-slope = $(T-W)S_x$
d_3 = flow depth at edge of inlet = $(T-W)S_x + (W - \text{grate width})S_w$

d_1 = (10.5 – 2.5)(0.02) + (2.5)(.05) = 0.285 feet

d_2 = (10.5 – 2.5)(0.02) = 0.16 feet

d_3 = (10.5 -2.5)(0.02) + (2.5 – 1.84)(.05) = 0.193 feet

Step B.2- Solve for (Q_t):

Q_t = total gutter flow (cubic feet per second)

$$Q_t = \frac{0.56\,S_L^{0.5}\,d_2^{2.67}}{n\,S_x} + \frac{0.56\,S_L^{0.5}\,(d_1^{2.67} - d_2^{2.67})}{n\,S_w} \qquad \begin{bmatrix}\text{Chapter 8 or Charts 2}\\ \text{and 5, Appendix H}\end{bmatrix}$$

$$Q_t = \frac{0.56\,(0.035)^{0.5}\,(0.16)^{2.67}}{(0.016)(0.02)} + \frac{0.56\,(0.035)^{0.5}\,(0.285^{2.67} - 0.16^{2.67})}{(0.014)(0.05)}$$

Q_t = 2.46 + 4.12 = 6.58 cubic feet per second

Step B.3- Solve for (Q_w):

Q_w = flow in width (W) or frontal flow, equal to the clogged grate width (in cubic feet per second)

$$Q_w = \frac{0.56\,S_L^{0.5}\,(d_1^{2.67} - d_3^{2.67})}{n\,S_w}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_w = \frac{0.56(0.035)^{0.5}\,(0.285^{2.67} - 0.193^{\,2.67})}{(0.014)(0.05)} = 3.39 \text{ cubic feet per second}$$

Step B.4- Solve for (V):

V = average gutter flow velocity (in feet per second)

$$V = \frac{Q_t}{A} = \frac{2\,Q_t}{T_s^2 S_x + W^2 S_w + 2WT_sS_x} = \frac{2\,Q_t}{\left[W(d_1 + d_2) + \dfrac{d_2^2}{S_x}\right]}$$ (**Chapter 8**)

$$V = \frac{2\,(6.58)}{(8)^2(0.02) + (2.5)^2\,(0.05) + 2(2.5)(8)(0.02)} = 5.50 \text{ feet per second}$$

Step B.5- Solve for (E_o):

E_o = the ratio of frontal flow to total gutter flow

$$E_o = \frac{Q_w}{Q_t} = \frac{3.39}{6.58} = 0.515$$ (Equation 4 or Chart 2, Appendix H)

Step B.6- Solve for (R_f):

R_f = the ratio of frontal flow intercepted to total frontal flow

R_f = 1 – 0.09 (V – V_o) (Equation 6 or Chart 1, Appendix H)

V = average flow velocity in the gutter (in feet per second)
V_o = gutter velocity where splash over first occurs (in feet per second)

V = 5.50 feet per second
V_o = 5.1 feet per second (per Chart 1, Appendix H, using 30 percent clogged grate length equal to 2.26 feet)

R_f = 1 – 0.09 (V – V_o)
R_f = 1 – 0.09 (5.50 – 5.1)
R_f = 0.96

R_f can not exceed 1.0, therefore,
R_f = 0.96

Step B.7- Solve for (R_s):

R_s = the ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\frac{0.15\,V^{1.8}}{S_x\,L^{2.3}}\right)}$$ (Equation 7 or Chart 4, Appendix H)

L = 2.26 feet (30 percent clogged grate length)

$$R_s = \frac{1}{1+\left(\frac{0.15\,(5.50)^{1.8}}{(0.02)(2.26)^{2.3}}\right)}$$

R_s = 0.039

Step B.8- Solve for (E):

E = the inlet interception efficiency

E = $R_f\,E_o + R_s\,(1 – E_o)$ (Equation 8)

E = (1.0)(0.489) + 0.039 (1 - 0.489)

E = 0.51

Okay (70 percent minimum efficiency criteria does not apply to Method B)

Step B.9- Solve for (L_1):

L_1 = first inlet from the crest

$$L_1 = \frac{43560\,Q_t}{C\,C_f\,\,i\,W_p}E \qquad \text{(Equation 1)}$$

i = 2.28 inches per hour (Assume 5-minute t_c using a 10-year storm design, Hydrologic Zone 8; use IDR curve in **Chapter 7**)

C = 0.90

C_f = 1.0 (per Appendix F, **Chapter 7**)

W_p = 24 feet (2 – 12-foot lanes) + 10.5-foot shoulder/gutter + 5-foot sidewalk + 7-foot median = 46.5 feet

E = 1.0

$$L_1 = \frac{43{,}560\,(6.58)}{(0.90)(1.0)(2.28)(46.5)}(1) = 3{,}004\text{ feet}$$

Step B.10- Solve for (L_2):

L_2 = distance to successive inlets

$$L_2 = \frac{43{,}560\,Q_i}{C\,C_f\,\,i\,W_p} \qquad \text{(Equation 1)}$$

Q_i = intercepted flow (in cubic feet per second)

Q_i = E Q_t = (0.51)(6.58) = 3.36 cubic feet per second

$$L_2 = \frac{43{,}560\,(3.36)}{(0.90)(1.0)(2.28)(46.5)} = 1{,}534\text{ feet}$$

L_2 = 400 feet, maximum distance to successive inlets (per Appendix D)

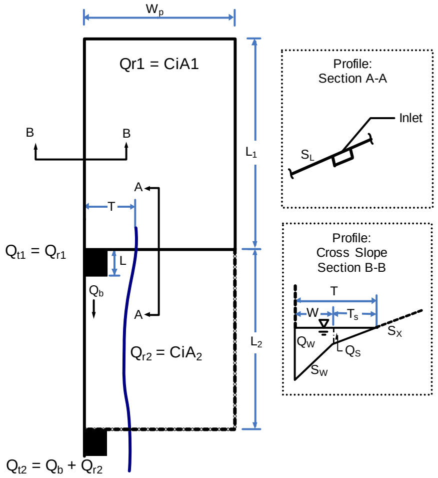
Therefore, L_1 = 3,004 feet and L_2 = 400 feet

Inlet Design Computation Sheet (Diagram B-B Process)

Given:

Surface Description	
Road Classification	Highway on-grade section (greater than or equal to 45 miles per hour)
Type of Curb and Gutter, see Chapter 8, Curbs and Gutters	Curb and Gutter
Surface Material	concrete gutter w/ pavement
Manning's Coefficient, n	0.014
Drainage Area Description	
Runoff Coefficient, C	0.9
Hydrologic Zone *(Chapter 7)*	8
Intensity (i) in/hr *(Chapter 7)*	2.28 in/hr, 5-minute T_c, 10-year design storm
C_f *(Chapter 7, Appendix F)*	1
Type of Inlet *(Chapter 13, Appendix C, Table B)*	G-2 Inlet with P-1 7/8 - 4 grate
Design Method: **Method A** ☑ **Method B** ☐	
Design Criteria:	
Method A (reference Section 2)	
Minimum Efficiency	70 Percent
Allowable spread *(Appendix D, Table A)*	shoulder + gutter
shoulder width	8.00 feet
distance into outside lane	0, but 2.5-foot gutter
spread (T) = Shoulder Width + Distance into outside lane	10.5 feet
Percentage Clogged	0%
Method B (reference Section 2)	
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	

Sketch:



Assume Spread								Calculate Hydrology			Calculate Inlet Efficiency			Locate Inlet					
Spread	Long. Slope	Cross Slope		Gutter Width	Total Gutter Flow	Design Inlet Length	Design Inlet Width	Flow from Contributing Area	Bypass Flow from Upstream Inlet	Total Flow	Inlet Interception Efficiency	Intercepted Flow	Bypass Flow	Drainage Length	Drainage Width	Drainage Area	Number	Station	Comments
T	S_L	S_x	S_w	W	Q_t	L_i	W_i	Q_r	Q_b	Q_t	E	Q_i	Q_b	L	W_p	A			
(ft)	(ft/ft)	(ft/ft)	(ft/ft)	(ft)	(cfs)	(ft)	(ft)	(cfs)	(cfs)	(cfs)		(cfs)	(cfs)	(ft)	(ft)	(ac)			
																		34+00	High point
10.50	0.035	0.02	0.05	2.50	6.07	2.67	2.25	6.07	0.00	6.07	0.59								Because E is less than 70 percent, more flow would bypass than allowed, reduce flow width and try again
8.50	0.035	0.02	0.05	2.50	3.75	2.67	2.25	3.75	0.00	3.75	0.70	2.63	1.12	1,711	46.50	1.83	2	16+89	First inlet from crest
8.50	0.035	0.02	0.05	2.50	3.75	2.67	2.25	2.63	1.12	3.75	0.70	2.63	1.12	1,200	46.50	1.28	1	12+89	This is the maximum distance (1,200 feet) allowed between catchbasins with bypass flows based on hydraulic conditions only; however, due to maintenance requirements, the maximum distance between catchbasins is 400 feet.

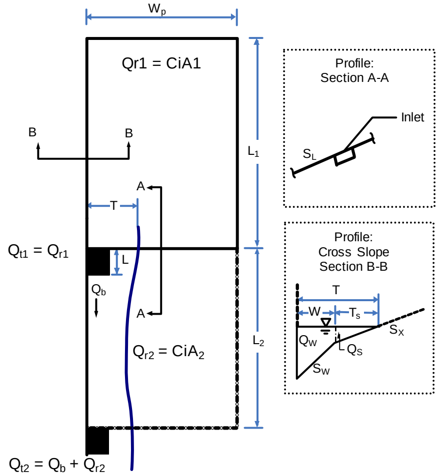
Figure 4a – Example Problem 5.1.1 (Diagram B-B, Method A)

Inlet Design Computation Sheet (Diagram B-B Process)

Given:

Surface Description	
Road Classification	Highway on-grade section (greater than or equal to 45 miles per hour)
Type of Curb and Gutter, see Chapter 8, Curbs and Gutters	Curb and Gutter
Surface Material	concrete gutter w/ AC
Manning's Coefficient, n	0.014
Drainage Area Description	
Runoff Coefficient, C	0.9
Hydrologic Zone *(Chapter 7)*	8
Intensity (i) in/hr *(Chapter 7)*	2.28 in/hr, 5-minute T_c, 10-year design storm
C_f *(Chapter 7, Appendix F)*	1
Type of Inlet *(Chapter 13, Appendix C, Table B)*	G-2 Inlet with P-1 7/8 - 4 grate
Design Method: **Method A** ☐ **Method B** ☑	
Design Criteria:	
Method A (reference Section 2)	
Minimum Efficiency	70 Percent
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	
Method B (reference Section 2)	
Allowable spread *(Appendix D, Table A)*	shoulder + gutter + 0 feet into lane
shoulder width	8.00 feet
distance into outside lane	0.00, but 2.5-foot gutter
spread (T) = Shoulder Width + Distance into outside lane	10.5 feet
Percentage Clogged	30%

Sketch:



Assume Spread								Calculate Hydrology			Calculate Inlet Efficiency			Locate Inlet					
Spread	Long. Slope	Cross Slope		Gutter Width	Total Gutter Flow	Design Inlet Length	Design Inlet Width	Flow from Contributing Area	Bypass Flow from Upstream Inlet	Total Flow	Inlet Interception Efficiency	Intercepted Flow	Bypass Flow	Drainage Length	Drainage Width	Drainage Area	Number	Station	Comments
T	S_L	S_x	S_w	W	Q_t	L_i	W_i	Q_r	Q_b	Q_t	E	Q_i	Q_b	L	W_p	A			
(ft)	(ft/ft)	(ft/ft)	(ft/ft)	(ft)	(cfs)	(ft)	(ft)	(cfs)	(cfs)	(cfs)		(cfs)	(cfs)	(ft)	(ft)	(ac)			
																		34+00	High point
10.50	0.035	0.02	0.05	2.50	6.07	2.26	1.84	6.07	0.00	6.07	0.51	3.10	2.97	2,771	46.50	2.96	2	6+29	First inlet from crest
10.50	0.035	0.02	0.05	2.50	6.07	2.26	1.84	3.10	2.97	6.07	0.51	3.10	2.97	1,415	46.50	1.51	1	2+29	This is the maximum distance (1,415 feet) allowed between catchbasins with bypass flows based on hydraulic conditions only; however, due to maintenance requirements, the maximum distance between catchbasins is 400 feet.

Figure 4b – Example Problem 5.1.1 (Diagram B-B, Method B)

5.2 Curb-Opening Inlets (On-grade)

Curb-opening inlets are effective in the drainage of highway pavements where flow depth at the curb is sufficient for the inlet to perform efficiently. Curb-openings are relatively free of clogging tendencies and offer little interference to traffic operation. They are a viable alternative to grates in many locations where grates would be in traffic lanes or would be hazardous for pedestrians or bicyclists.

Note:

- *Standard curb-opening inlets used in ODOT storm drainage systems are noted in Appendix C.*
- *Curb-opening inlets lose capacity rapidly with an increase in longitudinal grade.*

The length of curb-opening inlet required for total interception of gutter flow on a pavement section with a straight cross slope is expressed by:

$$L_T = 0.6\,Q_t^{0.42}\,S_L^{0.3}\left(\frac{1}{n\,S_x}\right)^{0.6} \qquad \text{(Equation 10)}$$

Where:

L_T = curb-opening length required to intercept 100 percent of the gutter flow in feet
S_x = cross slope in foot per foot
n = Manning's coefficient
Q_t = total gutter flow in cubic feet per second
S_L = longitudinal slope in foot per foot

The efficiency of curb-opening inlets shorter than the length required for total interception is expressed by:

$$E = 1 - \left(1 - \frac{L}{L_T}\right)^{1.8} \qquad \text{(Equation 11)}$$

Where:

L = curb-opening length in feet

Chart 6 in Appendix H is a nomograph for the solution of Equation 10, and Chart 7 (Appendix H) provides a solution of Equation 11.

The length of inlet required for total interception by depressed curb-opening inlets or curb-openings in depressed gutter sections can be found by the use of an equivalent cross slope (S_e) in Equation 12.

$$S_e = S_x + S'_w E_o \qquad \text{(Equation 12)}$$

Where:

S'_w = cross slope of the gutter measured from the cross slope of the pavement
= a/W in foot per foot
a = gutter depression in feet
W = width of the depressed gutter section (W = 2 feet for CG-3 inlets) in feet
E_o = ratio of flow in the depressed section to total gutter flow. It is determined by the gutter configuration upstream of the inlet.
S_x = roadway cross slope in foot per foot

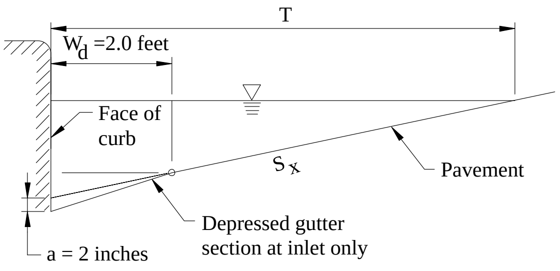
Note: S_e can be used to calculate the length of curb-opening by substituting S_e for S_x in Equation 10.

5.2.1 Curb-Opening Inlet (On-grade) Example

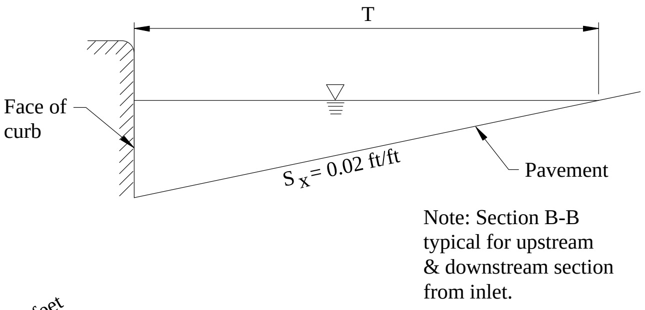
The following example illustrates the application of the inlet interception equation.

5.2.1.1 Determine location of first inlet and spacing of subsequent inlets

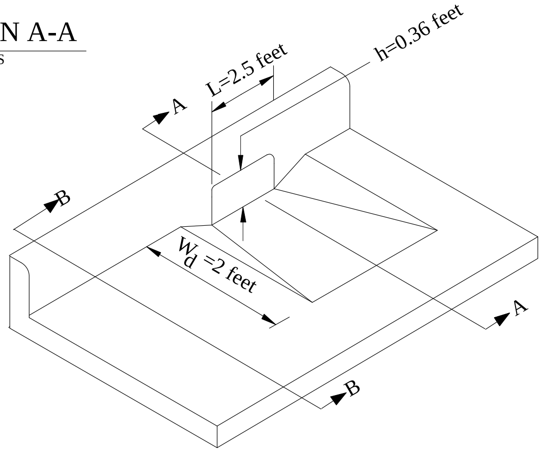
Sketch:



SECTION A-A
NTS



SECTION B-B
NTS



CURB OPENING INLET
NTS

Given:

- Highway on-grade section (less than 45 miles per hour)
- Standard Curb (reference **Chapter 8**)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- S_x = 0.02 foot per foot (roadway cross slope)
- S_L = 0.0025 foot per foot (roadway longitudinal slope)
- W_p = 31 feet (width of contributing drainage area, 2 – 12-foot lanes with 7-foot shoulder)
- CG-3 inlet (reference Table B, Appendix C)
- h = 0.36 feet (curb opening height for CG-3 inlet, see sketch above)
- L = 2.5 feet (curb opening length for CG-3 inlet, see sketch above)
- a = 2 inches (inlet depression, see sketch above)
- W_d = 2 feet (width of depressed gutter section)
- C = 0.90 (rational method runoff coefficient for pavement)
- 10-year design, Salem area (IDR curves are located in **Chapter 7**)

Criteria:

- Allowable spread is 2 feet into the outside lane (per Table A for highway on-grade section; less than 45 miles per hour)
- Therefore; T = allowable spread = shoulder width + 2 feet
  = 7 feet + 2 feet = 9 feet
- E = 0.70 (minimum efficiency for Method A)
- L_2 = 400 feet (maximum distance between successive inlets, reference Section 2, Appendix D)

5.2.1.2 Method A

Solution:

Step A.1- Solve for (Q_t):

Q_t = total gutter flow (cubic feet per second). The approach gutter section to the inlet is used to calculate the total flow

$$Q_t = \frac{0.56}{n}(S_x)^{1.67}\,(S_L)^{0.5}\,(T)^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_t = \frac{0.56}{.016}(0.02)^{1.67}\,(0.0025)^{0.5}\,(9)^{2.67}$$

Q_t = 0.90 cubic feet per second

Step A.2- Solve for (E_o):

E_o = ratio of flow in the depressed section to total gutter flow

$$E_o = 1-\left(1-\frac{W_d}{T}\right)^{2.67} = 1-\left(1-\frac{2}{9}\right)^{2.67} = 0.489 \qquad \left[\begin{array}{r}\text{Equation 4 or Chart 2,}\\ \text{Appendix H}\end{array}\right]$$

Step A.3- Solve for (S_e):

S_e = equivalent cross-slope (foot per foot)

$S'_w = \frac{a}{W_d}$ (cross slope of the depressed gutter measured from the cross slope of the pavement, S_x)

a = 2 inches for CG-3 inlets (gutter depression)

W_d = 2 feet for CG-3 inlets (width of the depressed gutter section)

$$S'_w = \frac{\left(\frac{2\text{ in}}{12\text{ in/ft}}\right)}{2\text{ ft}} = 0.0833\text{ foot per foot}$$

$S_e = S_x + S'_W E_o$ (Equation 12)

$S_e = 0.02 + (0.0833)(0.489) = 0.0607$

Step A.4- Solve for (L_T):

L_T = curb-opening length required to intercept 100 percent of the gutter flow

$$L_T = 0.6\,Q^{0.42} S_L^{0.3\cdot}\left(\frac{1}{n\,S_e}\right)^{0.6}$$ (S_e is substituted for S_x in Equation 10)

$$L_T = 0.6\,(0.90)^{0.42}\,(0.0025)^{0.3}\left(\frac{1}{(0.016)(0.0607)}\right)^{0.6} = 6.11\text{ feet}$$

Step A.5- Solve for (E):

E = the curb-opening interception efficiency

$$E = 1 - \left(1 - \frac{L}{L_T}\right)^{1.8}$$ (Equation 11 or Chart 7, Appendix H)

L = 2.5 feet (curb-opening length)

$$E = 1 - \left(1 - \frac{2.5}{6.11}\right)^{1.8}$$

E = 0.612

The curb-opening interception efficiency (E) is less than 0.70 therefore, more than 30 percent would bypass the inlet. A narrower flow width (T) would be assumed and steps 1 through 5 would be repeated until the minimum efficiency of 0.70 is obtained.

Try T = allowable spread = 8 feet

Step A1.2- Solve for (Q_t):

Q_t = total flow in shoulder and gutter (cubic feet per second)

$$Q_t = \frac{0.56}{n}(S_x)^{1.67}(S_L)^{0.5}(T)^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_t = \frac{0.56}{0.016}(0.02)^{1.67}(0.0025)^{0.5}(8)^{2.67}$$

Q_t = 0.66 cubic feet per second

Step A2.2- Solve for (E_o):

$$E_o = 1-\left(1-\frac{W_d}{T}\right)^{2.67}$$ (Equation 4 or Chart 2, Appendix H)

$$E_o = 1-\left(1-\frac{2}{8}\right)^{2.67} = 0.536$$

Step A3.2- Solve for (S_e):

$S_e = S_x + S'_W E_o$ (Equation 12)

$S_e = 0.02 + (0.0833)(0.536) = 0.0646$

Step A4.2- Solve for (L_T):

$$L_T = 0.6\,Q^{0.42}\,S_L^{0.3}\left(\frac{1}{n\,S_e}\right)^{0.6}$$ (S_e is substituted for S_x in Equation 10)

$$L_T = 0.6\,(.66)^{0.42}(0.0025)^{0..3}\left[\frac{1}{(.016)\,(.0646)}\right]^{0.6} = 5.17\text{ feet}$$

Step A5.2- Solve for (E):

$$E = 1-\left(1-\frac{L}{L_T}\right)^{1.8}$$ (Equation 11 or Chart 7, Appendix H)

$$E = 1-\left(1-\frac{2.5}{5.16}\right)^{1.8} = 0.70\ \text{Okay}$$

Step A6.2- Solve for (L_1):

L_1 = first inlet from the crest

$$L_1 = \frac{43{,}560\,Q_t}{C\ \ C_f\ i\,W_p}E$$ (Equation 1)

i = 2.10 inches per hour (Salem area, assume 5 minute t_c using a 10-year storm design)

C = 0.90

C_f = 1.0 (per **Chapter 7**, Appendix F)

W_p = 24 feet (2 – twelve foot lanes) + 7 foot shoulder = 31 feet

E = 1.0

$$L_1 = \frac{43{,}560\,(0.66)}{(0.90)(1.0)(2.10)(31)}(1) = 490 \text{ feet}$$

Step A7.2- Solve for (L_2):

L_2 = distance to successive inlets

$$(1)\ L_2 = \frac{43{,}560\,Q_i}{C\ C_f\ i\ W_p} \qquad \text{(Equation 1)}$$

$$(2)\ L_1 = \frac{43{,}560\,Q_t}{C\ C_f\ i\ W_p} \qquad \text{(Equation 1)}$$

$$(3)\ Q_i = EQ_t \qquad \text{(Equation 9)}$$

Substituting $Q_i = EQ_t$ into Equation 1 and equating Equations 1 and 2 simplifies to:

L_2 = (E) (L_1)

L_2 = (0.70)(490) = 343 feet

Therefore L_1 = 490 feet and L_2 = 343 feet

5.2.1.3 Method B

Criteria:

- Allowable spread is 2 feet into the outside lane (per Table A for highway on-grade section; less than 45 miles per hour)
- T = shoulder width + 2 feet
  = 7 feet + 2 feet
  = 9 feet (total allowable spread, per Table A)
- Assume 30 percent clogged (per Table A)
- Curb-opening inlet 30 percent clogged:
- h = 0.36 feet (curb opening height for CG-3 inlet, 30 percent clogged per Table B)
- L = 1.75 feet (curb opening length for CG-3 inlet, 30 percent clogged per Table B)
- L_2 = 400 feet (maximum distance between successive inlets, reference Section 2, Appendix D)

Step B.1- Solve for (Q_t):

$$Q_t = \frac{0.56}{n}(S_x)^{1.67}(S_L)^{0.5}(T)^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_t = \frac{0.56}{0.016}(0.02)^{1.67}(0.0025)^{0.5}(9)^{2.67}$$

Q_t = 0.90 cubic feet per second

Step B.2- Solve for (E_o):

$$E_o = 1-\left(1-\frac{W_d}{T}\right)^{2.67} = 1-\left(1-\frac{2}{9}\right)^{2.67} = 0.489$$ $\left[\begin{array}{r}\text{Equation 4 or Chart 2,}\\ \text{Appendix H}\end{array}\right]$

Step B.3- Solve for (S_e):

$$S_w^{'} = \frac{a}{W_d}$$

a = 2 inches for CG-3 inlets (gutter depression)

W_d = 2 feet for CG-3 inlets (width of the depressed gutter section)

$$S_w^{'} = \frac{\left(\frac{2\text{ in}}{12\text{ in/ft}}\right)}{2\text{ ft}} = 0.0833\text{ foot per foot}$$

$S_e = S_x + S'_W E_o$ (Equation 12)

$S_e = 0.02 + (0.0833)(0.488) = 0.0607$

Step B.4- Solve for (L_T):

$$L_T = 0.6\,Q^{0.42}\,S_L^{0.3}\left(\frac{1}{n\,S_e}\right)^{0.6}$$ (S_e is substituted for S_x in Equation 10)

$$L_T = 0.6\,(0.90)^{0.42}\,(0.0025)^{0.3}\left(\frac{1}{(0.016)\,(0.0607)}\right)^{0.6}$$

L_T = 6.11 feet

Step B.5- Solve for (E):

$$E = 1-\left(1-\frac{L}{L_T}\right)^{1.8}$$ (Equation 11 or Chart 7, Appendix H)

L = 1.75 feet (30 percent clogged curb-opening length)

$$E = 1 - \left(1 - \frac{1.75}{6.11}\right)^{1.8}$$

$$E = 0.456$$

Okay (70 percent minimum efficiency criteria does not apply to method B)

Step B.6- Solve for (L_1):

L_1 = first inlet from the crest

$$L_1 = \frac{43{,}560\,Q_t}{C\ C_f\ i\,W_p}\,E \qquad \text{(Equation 1)}$$

i = 2.10 inches per hour (10-year precipitation intensity for Salem area)
C = 0.90
C_f = 1.0 (per **Chapter 7**, Appendix F)
W_p = 24 feet (2 – 12-foot lanes) + 7-foot shoulder = 31 feet
E = 1.0

$$L_1 = \frac{43{,}560\,(0.90)}{(0.90)(1.0)(2.10)(31)}\,(1) = 669\ \text{feet}$$

Step B.7- Solve for (L_2):

L_2 = distance to successive inlets

L_2 = (E) (L_1) = (0.456) (669 feet) = 304 feet

5.3 Slotted Inlets (On-grade)

Slotted inlets are effective pavement drainage inlets which have a variety of applications. They can be used on curbed or uncurbed sections and offer little interference to traffic operations. They can be placed longitudinally in the gutter or transversely to the gutter. Slotted inlets should be connected into inlet structures or provide clean-out ports on both ends for maintenance access in case of plugging or freezing.

The minimum cleanout velocity of 3 feet per second should be provided for slotted drain systems. A minimum slope of 0.89 percent for an 18-inch corrugated pipe and 1.5 percent slope for a 12-inch diameter corrugated pipe would provide the desired velocity of 3 feet per second. The designer should assume 50 percent clogging when using inlet design method B, which will result in twice the calculated required length for flow interception because slotted inlets tend to plug.

Note: Standard slotted inlet used in ODOT Storm drain systems is noted in Appendix C

5.3.1 Longitudinal Placement

Flow interception by slotted inlets and curb-opening inlets is similar in that each is a side weir and the flow is subjected to lateral acceleration due to the cross slope of the pavement. Slotted inlets may have economic advantages in some cases and could be very useful on widening and safety projects where right of way is narrow and existing inlet capacity must be supplemented. It is much less expensive to add length to an existing slotted inlet to increase interception capacity than it is to add length to an existing curb-opening inlet. In some cases curbs could be eliminated as a result of utilizing slotted inlets.

The Federal Highway Administration has performed tests of slotted inlets with 1.75 inch slot widths and these tests have determined that the length of slotted inlet required for total interception can be computed by Equation 10. Therefore, Chart 6 should be used to evaluate slotted inlets. Equation 11 is also applicable to slotted inlets and Chart 7 can be used to obtain the inlet efficiency for the selected length of slotted inlet.

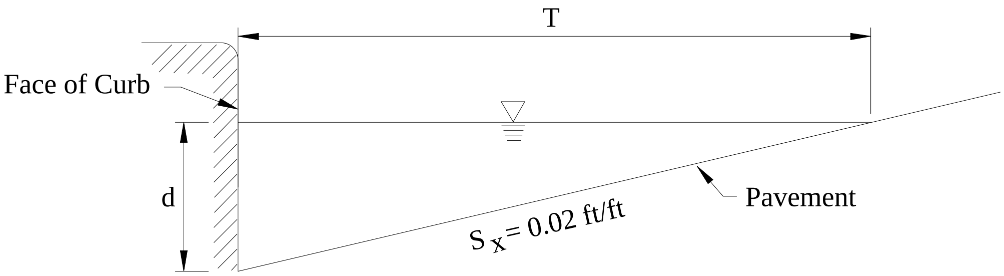
Note: The determination of total interception and efficiencies are the same for slotted and curb-opening inlets. Therefore, the equations and figures used for the design of curb-opening inlets should be used in the design of slotted inlets. When using Equation 10 for slot inlet design, it should only be used with a slot width of 1.75 inches.

5.3.2 Slotted Inlet (On-grade) Example

The following example illustrates the application of the inlet efficiency equations for slotted inlets.

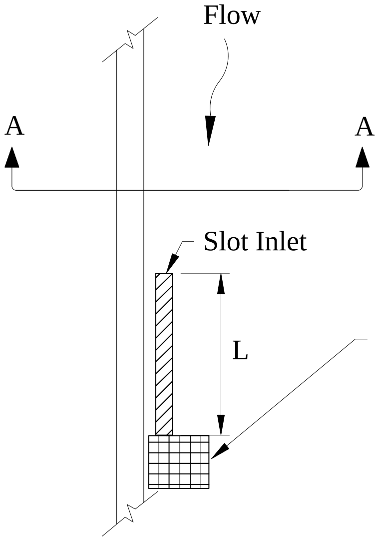
5.3.2.1 Determine the inlet interception efficiency (E), the intercepted flow (Q_i), and bypass flow (Q_b) for the following conditions:

Sketch:



SECTION A-A

NTS



Grate Inlet
(ignored throughout this example. Emphasis is on analyzing a slotted inlet. Inlet is needed at downsteam end of slotted inlet to function as a junction and cleanout)

SLOTTED INLET

NTS

Given:

- Collector road, on-grade section, less than 45 miles per hour
- Standard Curb
- Longitudinal placement of a slotted inlet adjacent to curb.
- L = 10 feet (slotted inlet length)
- S_L = 0.01 foot per foot (roadway longitudinal slope)
- S_x = 0.02 foot per foot (roadway cross slope)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- 10-year design storm, Hydraulic Zone 8 (IDR curves located in **Chapter 7**)
- W_p = 31 feet (width of contributing area, 2 – 11.5 foot lanes with 8-foot shoulder)
- L_2 = 400 feet (distance to upstream catch basin)
- i = 2.28 inches per hour (Salem area, assume 5 minute time of concentration, using a 10-year storm)

5.3.2.2 Method A

Criteria:

- Bypass flow is limited to a maximum of 30 percent
- Assume no clogging, therefore L = 10 feet (slotted inlet length)
- T = shoulder width + 2 feet
  = 8 feet + 2 feet
  = 10 feet (total allowable spread per Table A)
- E = 0.70 (minimum efficiency for Method A)

Solution:

Step A.1- Solve for (Q_{10}):

Q_{10} = flowrate to slotted inlet in cubic feet per second

Q = CiA (**Chapter 7**)

A = (400)(31) = 12,400 square feet = 0.28 acres

Q = (0.90)(2.28)(0.28) = 0.57 cubic feet per second

Step A.2- Solve for (T):

T = total spread at the slotted inlet (**Chapter 8**)

$$T = \left(\frac{Q_{10} n}{0.56 (S_L)^{0.5} (S_X)^{1.67}} \right)^{0.375}$$

$$T = \left(\frac{(0.57)(0.016)}{0.56 (0.01)^{0.5} (0.02)^{1.67}} \right)^{0.375} = 5.9 \text{ feet}$$

Spread at the slotted inlet = 5.9 feet

Allowable spread = 10 feet.

Placing this slotted inlet 400 feet downstream is acceptable because maximum spread (5.9 feet) is less then the allowable spread (10 feet).

Step A.3- Solve for (L_T):

L_T = length of opening to intercept 100 percent of the gutter flow in feet

$$L_T = 0.6 Q_{10}^{0.42} S_L^{0.30} \left(\frac{1}{n S_x} \right)^{0.6} \quad \text{(Equation 10)}$$

L_T = $0.6(0.57)^{0.42}(0.01)^{0.30}\left(\frac{1}{(0.016)(0.02)}\right)^{0.6}$

L_T = 14.9 feet

Step A.4- Solve for (E):

E = inlet interception efficiency

$$E = 1-\left(1-\frac{L}{L_T}\right)^{1.8} \qquad \text{(Equation 11)}$$

$$E = 1-\left(1-\frac{10}{14.9}\right)^{1.8} = 0.86$$

E = 86 percent

Okay, 70 percent minimum efficiency criteria is satisfied.

Step A.5 Solve for (Q_i):

Q_i = intercepted flow
Q_i = EQ (Equation 9)
= (0.86)(0.57) = 0.49 cubic feet per second

Step A.6 Solve for (Q_b):

Q_b = flow that is not intercepted by the slotted inlet and must be included in the evaluation of downstream gutter and inlet
Q_b = Q - Q_i (Equation 3)
Q_b = 0.57 – 0.49 = 0.08 cubic feet per second

5.3.2.3 Method B

Criteria:

- Assume 50 percent clogging per Table A, therefore L = 10(0.50) = 5 feet
- T = shoulder width + 2 feet
  = 8 feet + 2 feet
  = 10 feet (total allowable spread per Table A)

Step B.1- Solve for (Q_{10}):

Q_{10} = flowrate to slotted inlet in cubic feet per second

Q = CiA (**Chapter 7**)

A = (400)(31) = 12,400 square feet = 0.28 acres

Q = (0.90)(2.28)(0.28) = 0.57 cubic feet per second

Step B.2- Solve for (T):

T = total spread at the slotted inlet (**Chapter 8**)

$$T = \left(\frac{Q_{10}n}{0.56(S_L)^{0.5}(S_X)^{1.67}}\right)^{0.375}$$

$$T = \left(\frac{(0.57)(0.016)}{0.56(0.01)^{0.5}(0.02)^{1.67}}\right)^{0.375} = 5.9 \text{ feet}$$

Spread at the slotted inlet = 5.9 feet

Allowable spread = 10 feet.

Placing this slotted inlet 400 feet downstream is acceptable because maximum spread is (5.9 feet) less than allowable spread (10 feet).

Step B.3- Solve for (L_T):

L_T = length of opening to intercept 100 percent of the gutter flow in feet

$$L_T = 0.6Q_{10}^{0.42} S_L^{0.30}\left(\frac{1}{nS_x}\right)^{0.6} \quad \text{(Equation 10)}$$

$$L_T = 0.6(0.57)^{0.42}(0.01)^{0.30}\left(\frac{1}{(0.016)(0.02)}\right)^{0.6}$$

L_T = 14.9 feet

Step B.4- Solve for (E):

E = inlet interception efficiency

L = 5 feet (50 percent clogged slotted inlet length)

$$E = 1-\left(1-\frac{L}{L_T}\right)^{1.8} \quad \text{(Equation 11)}$$

$$E = 1-\left(1-\frac{5}{14.9}\right)^{1.8} = 0.52$$

E = 52 percent

Okay, 70 percent minimum efficiency criteria does not apply to Method B

Step B.5 Solve for (Q_i):

Q_i = intercepted flow
Q_i = EQ (Equation 9)
= (0.52)(0.57) = 0.3 cubic feet per second

Step B.6 Solve for (Q_b):

Q_b = flow that is not intercepted by the slotted inlet and must be included in the evaluation of downstream gutter and inlet

Q_b = $Q - Q_i$ (Equation 3)

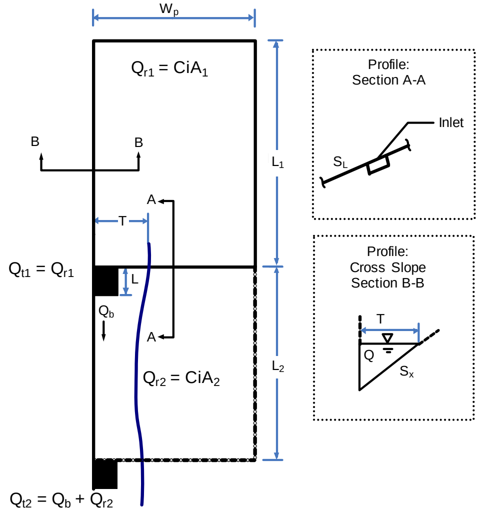
Q_b = 0.57 – 0.3 = 0.27 cubic feet per second

Inlet Design Computation Sheet (Diagram A-A Process)

Given:

Surface Description	
Road Classification	Collector road, on grade, less than 45 miles per hour
Type of Curb and Gutter, see Chapter 8, Curbs and Gutters	Standard Curb
Surface Material	asphalt
Manning's Coefficient, n	0.016
Drainage Area Description	
Runoff Coefficient, C	0.9
Hydrologic Zone *(Chapter 7)*	8
Intensity (i) in/hr *(Chapter 7)*	2.28 in/hr, 5-minute T_c, 10-year design storm
C_f *(Chapter 7, Appendix F)*	1
Type of Inlet *(Chapter 13, Appendix C, Table B)*	slotted inlet
Design Method: **Method A** ☑ **Method B** ☐	
Design Criteria:	
Method A **(reference Section 2)**	
Minimum Efficiency	70 Percent
Allowable spread *(Appendix D, Table A)*	shoulder + 2 feet
shoulder width	8.00 feet
distance into outside lane	2.00
spread (T) = Shoulder Width + Distance into outside lane	10.00 feet
Percentage Clogged	0%
Method B **(reference Section 2)**	
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	

Sketch:



Locate Inlet			Calculate Hydrology			Calculate Spread								Calculate Inlet Efficiency					
Drainage Length	Drainage Width	Drainage Area	Flow from Contributing Area	Bypass Flow from Upstream Inlet	Total Flow	Spread	Long. Slope	Cross Slope		Gutter Width	Total Gutter Flow	Design Inlet Length	Design Inlet Width	Inlet Interception Efficiency	Intercepted Flow	Bypass Flow	Number	Station	Comments
L	W_p	A	Q_r	Q_b	Q_t	T	S_L	S_x	S_w	W	Q_t	L_i	W_i	E	Q_i	Q_b			
(ft)	(ft)	(ac)	(cfs)	(cfs)	(cfs)	(ft)	(ft/ft)	(ft/ft)	(ft/ft)	(ft)	(cfs)	(ft)	(ft)		(cfs)	(cfs)			
400	31.00	0.28	0.57	0.00	0.57	5.90	0.0100	0.02	N/A	N/A	0.57	10.00	0.15	0.86	0.49	0.08	1	4+00	Efficiency is greater than minimum and spread is less than allowable.

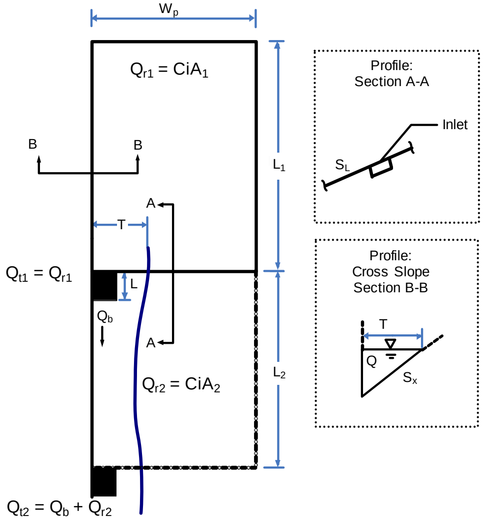
Figure 5a – Example Problem 5.3.2 (Diagram A-A, Method A)

Inlet Design Computation Sheet (Diagram A-A Process)

Given:

Surface Description	
Road Classification	Collector road, on grade, less than 45 miles per hour
Type of Curb and Gutter, see Chapter 8, Curbs and Gutters	Standard Curb
Surface Material	asphalt
Manning's Coefficient, n	0.016
Drainage Area Description	
Runoff Coefficient, C	0.9
Hydrologic Zone *(Chapter 7)*	8
Intensity (i) in/hr *(Chapter 7)*	2.28 in/hr, 5-minute T_c, 10-year design storm
C_f *(Chapter 7, Appendix F)*	1
Type of Inlet *(Chapter 13, Appendix C, Table B)*	slotted inlet
Design Method: Method A ☐ **Method B** ☑	
Design Criteria:	
Method A (reference Section 2)	
Minimum Efficiency	70 Percent
Allowable spread *(Appendix D, Table A)*	
shoulder width	
distance into outside lane	
spread (T) = Shoulder Width + Distance into outside lane	
Percentage Clogged	
Method B (reference Section 2)	
Allowable spread *(Appendix D, Table A)*	shoulder + 2.00 feet ft into outside lane
shoulder width	8.00 feet
distance into outside lane	2.00 feet
spread (T) = Shoulder Width + Distance into outside lane	10.00 feet
Percentage Clogged	50%

Sketch:



Locate Inlet			Calculate Hydrology			Calculate Spread								Calculate Inlet Efficiency					
Drainage Length	Drainage Width	Drainage Area	Flow from Contributing Area	Bypass Flow from Upstream Inlet	Total Flow	Spread	Long. Slope	Cross Slope		Gutter Width	Total Gutter Flow	Design Inlet Length	Design Inlet Width	Inlet Interception Efficiency	Intercepted Flow	Bypass Flow	Number	Station	Comments
L	W_p	A	Q_r	Q_b	Q_t	T	S_L	S_x	S_w	W	Q_t	L_i	W_i	E	Q_i	Q_b			
(ft)	(ft)	(ac)	(cfs)	(cfs)	(cfs)	(ft)	(ft/ft)	(ft/ft)	(ft/ft)	(ft)	(cfs)	(ft)	(ft)		(cfs)	(cfs)			
400	31.00	0.28	0.57	0.00	0.57	5.90	0.01	0.02	N/A	N/A	0.57	5.00	0.15	0.52	0.30	0.27	1	4+00	Efficiency is greater than minimum and spread is less than allowable.

Figure 5b – Example Problem 5.3.2 (Diagram A-A, Method B)

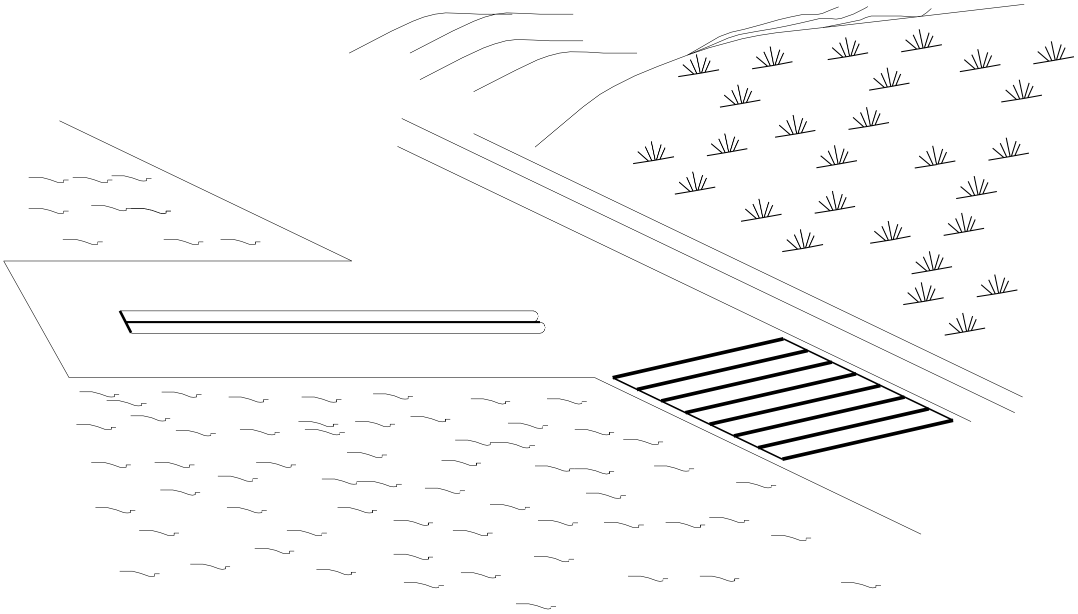
5.3.3 Transverse Placement

A slotted vane drain can be installed in conjunction with a grate inlet at locations where it is necessary to capture virtually all of the pavement runoff. The ideal installation would utilize a grate inlet to capture the flow in the gutter and the slotted vane drain to collect the flow extending into the shoulder.

Slotted vane drains should be designed by considering one of the following options:

- when a slotted vane drain is installed perpendicular to flow, use 0.075 cubic feet per second per lineal foot on longitudinal slopes of 0 percent to 6 percent, or
- obtain capacity curves from a manufacturer to aid in design

Note: A slotted vane drain is shaped and rounded to increase inlet efficiency and should not be confused with a standard vertical riser type slotted inlet (ODOT standard drawing No. RD 328).



Slotted Vane Drain (traverse placement)

5.4 Combination Inlets (On-grade)

Combination inlets consist of a grate and curb-opening. The two combination inlets commonly used in storm drainage design are equal length inlets and sweeper inlets.

Equal length inlets refer to a grate inlet placed along side a curb-opening inlet and both have the same length. Standard ODOT inlets CG-1 and CG-2 are equal length inlets as noted in

Appendix C. On-grade equal length combination inlets interception capacity is no greater than that of an on grate inlet because the capacity is computed by neglecting the curb-opening.

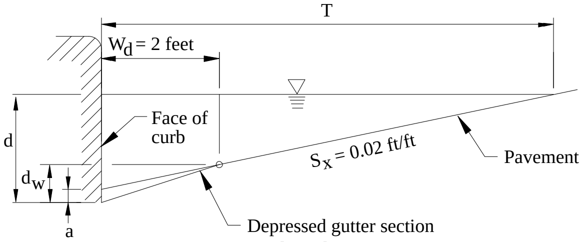
A sweeper inlet refers to a grate inlet placed at the downstream end of a curb-opening extension. Standard ODOT inlets CG-1 and CG-2 can be modified to include a curb-opening extension as noted in Appendix C. The curb-opening in a sweeper inlet is longer than the grate and intercepts gutter flow before the flow reaches the grate. The curb-opening extension has the ability to intercept any debris which might otherwise clog the grate inlet. The interception capacity of sweeper inlets is equal to the sum of the curb-opening upstream of the grate plus the grate capacity.

5.4.1 Sweeper Combination Inlet (On-grade) Example

The following example illustrates the computation of interception capacity and spacing of a sweeper combination inlet.

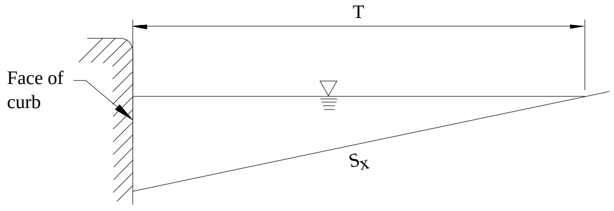
5.4.1.1 Determine maximum allowable flow, interception flow, bypass flow, location of first inlet, and spacing of subsequent inlets

Sketch:

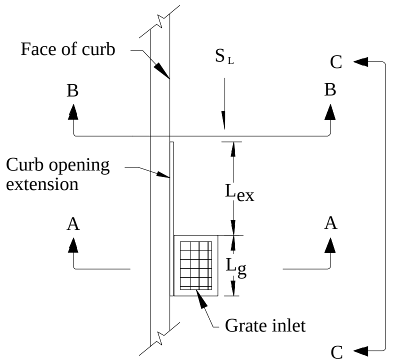


d = Flow Depth at curb
d_w = Flow Depth in gutter depression

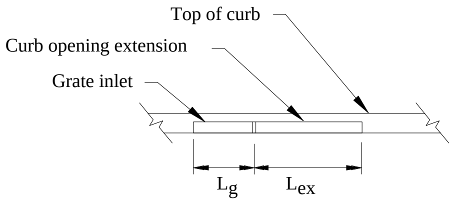
SECTION A-A
NTS



SECTION B-B
NTS



SWEEPER COMBINATION INLET
NTS



SECTION C-C
NTS

Given:

- S_x = 0.02 foot per foot (roadway cross slope)
- a = 1.5 inches (inlet depression only)
- CG-1 inlet with P-$1^7/_8$-4 grate (reference Table B, Appendix C)
- W_g = 1.75 feet (CG-1 grate width)
- L_g = 2.67 feet (CG-1 grate length)
- L_{ex} = 6 feet (curb opening extension length, reference Table B, Appendix C)
- h_{ex} = 0.33 feet (curb-opening height for curb opening extension)
- S_L = 0.0125 foot per foot (roadway longitudinal slope)
- Highway on-grade section (less than 45 miles per hour)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- Standard Curb (reference **Chapter 8**)
- W_p = 46.5 feet (width of contributing area, 2 – 12-foot lanes with 10.5-foot shoulder/gutter, 5-foot sidewalk, 7-foot median)
- W_d = 2 feet (width of the depressed gutter section, at inlet only)
- 10-year design, hydrologic zone 8 (IDR curves located in **Chapter 7**)

5.4.1.2 Method A

Criteria:

- T = allowable spread = shoulder width + 2 feet
  = 10.5 feet + 2 feet
  = 12.5 feet (reference Table A, Appendix D)
- E = 0.70 (minimum efficiency for Method A)
- L_2 = 400 feet (maximum distance between successive inlets. Reference Section 2, Appendix D)

Solution:

Step A.1- Solve for (Q_t):

Q_t = total gutter flow (cubic feet per second) - the approach gutter section to the inlet is used to calculate the total flow.

T = 12.5 feet (flow width in shoulder)

$$Q_t = \frac{0.56}{n} S_x^{1.67} S_L^{0.5} T^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_t = \frac{0.56}{0.016}(0.02)^{1.67}(0.0125)^{0.5}(12.5)^{2.67} = 4.82 \text{ cubic feet per second}$$

Step A.2- Solve for (E_o):

E_o = ratio of flow in the depressed section to total gutter flow

$$E_o = 1-\left(1-\frac{W}{T}\right)^{2.67} = 1-\left(1-\frac{2}{12.5}\right)^{2.67} = 0.372 \qquad \left[\begin{array}{r}\text{Equation 4 or Chart 2,}\\ \text{Appendix H}\end{array}\right]$$

Step A.3- Solve for (S_e):

S_e = equivalent cross-slope (foot per foot)

$$S'_w = \frac{a}{W_d}$$

a = 1.5 inches (gutter depression per standard drawing No. RD 366)

W_d = 2 feet (width of the depressed gutter section)

$$S'_w = \frac{\left(\frac{1.5\text{ in}}{12\text{ in/ft}}\right)}{2\text{ ft}} = 0.0625\text{ foot per foot}$$

S_e = $S_x + S'_W E_o$ (Equation 12)

S_e = 0.02 + (0.0625)(0.372) = 0.0432

Step A.4- Solve for (L_T):

L_T = curb-opening length required to intercept 100 percent of gutter flow

$$L_T = 0.6Q_t^{0.42}S_L^{0.3}\left(\frac{1}{nS_e}\right)^{0.6}$$ (S_e substituted for S_x in Equation 10)

$$L_T = 0.6(4.82)^{0.42}(0.0125)^{0.3}\left(\frac{1}{(0.016)(0.0432)}\right)^{0.6} = 24.5\text{ feet}$$

Step A.5- Solve for (E):

E = efficiency of curb opening extension (curb opening adjacent to grate is ignored throughout this example)

$$E = 1-\left(1-\frac{L_{ex}}{L_T}\right)^{1.8}$$ (Equation 11 or Chart 7, Appendix H)

L_{ex} = length of curb-opening extension (reference standard drawing No. RD 366)

L_{ex} = 6 feet

$$E = 1-\left(1-\frac{6.0}{24.5}\right)^{1.8} = 0.396 = 39.6\text{ percent}$$

Step A.6- Solve for (Q_{iex})

Q_{iex} = flow intercepted by curb-opening extension

Q_{iex} = EQ_t
= (0.396)(4.82) = 1.91 cubic feet per second

Step A.7- Solve for (Q_b):

Q_b = bypass flow from curb-opening extension and total flow toward grate inlet

Q_b = $Q_t - Q_{iex}$

= 4.82 – 1.91 = 2.91cubic feet per second

Step A.8- Solve for (T):

T = total spread at grate (after interception by curb-opening extension)

This is done by trial and error. Start by assuming an initial value of T = 10.35 feet.

T_s = T – W = 10.35 – 2.0 = 8.35 feet

$$Q_s = \frac{0.56}{n} S_x^{1.67} S_L^{0.5} T_s^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_s = \frac{0.56}{0.016}(0.02)^{1.67}(0.0125)^{0.5}(8.35)^{2.67} = 1.65 \text{ cubic feet per second}$$

$$E_o = 1 - \left(1 - \frac{W}{T}\right)^{2.67} = 1 - \left(1 - \frac{2}{10.35}\right)^{2.67} = 0.436 \quad \left[\begin{array}{r}\text{Equation 4 or Chart 2,}\\ \text{Appendix H}\end{array}\right]$$

$$Q_t = \frac{Q_s}{1 - E_o} = \frac{1.65}{1 - 0.436} = 2.93 \text{ cubic feet per second}$$

Bypass flow from curb opening extension is 2.91 cubic feet per second. Total flow toward catch basin grate at a spread of 10.35 feet is 2.93 cubic feet per second. Therefore, the spread at the catch basin grate is 10.35 feet.

Step A.9- Solve for (V):

V = average gutter flow velocity at grate (feet per second)

$$V = \frac{Q_t}{A} = \frac{2Q_t}{T^2 S_x}$$ (**Chapter 8**)

$$V = \frac{2\,(2.91)}{(10.35)^2\,(0.02)} = 2.72 \text{ feet per second}$$

Step A.10- Solve for (R_f)

R_f = ratio of frontal flow intercepted to total frontal flow

R_f = $1 – 0.09 (V – V_o)$ (Equation 6 or Chart 1, Appendix H)

V_o = gutter velocity where splash over first occurs (in feet per second)

CG-1 grate length = 2.67 feet

Grate type = P-1-$^7/_8$-4

From Chart 1 (Appendix H) V_o = 5.9 feet per second

R_f = $1 – 0.09 (2.72 – 5.9) = 1.29$

R_f can not exceed 1.0, therefore

R_f = 1.0

Step A.11- Solve for (R_s)

R_s = ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)}$$ (Equation 7 or Chart 4, Appendix H)

$$R_s = \frac{1}{1+\left(\frac{0.15\,(2.72)^{1.8}}{0.02(2.67)^{2.3}}\right)} = 0.17$$

Step A.12- Solve for (E_g):

E_g = interception efficiency of the inlet grate

E_g = $R_f E_o + R_s (1 – E_o)$ (Equation 8)

E_g = (1.0)(0.436) + 0. 17(1 – 0.436) = 0.53 = 53 percent

Step A.13- Solve for (Q_{ig}):

Q_{ig} = flow intercepted by grate inlet

Q_t = 2.91 cubic feet per second (bypass flow from curb opening extension and is total flow toward grate inlet)

Q_{ig} = $E_g Q_t$ = 0.53(2.91) = 1.54 cubic feet per second

Step A.14- Solve for (Q_i):

Q_i = total interception flow (both grate inlet and curb-opening extension)

Q_i = interception flow of curb-opening extension (Q_{iex}) + interception flow of grate inlet (Q_{ig})

Q_i = $Q_{iex} + Q_{ig}$

= 1.91 + 1.54 = 3.45 cubic feet per second

Step A.15- Solve for (E):

E = combination inlet efficiency

$$E = \frac{Q_i}{Q_t} = \frac{3.45}{4.82} = 0.72 = 72 \text{ percent}$$

Okay, 70 percent minimum efficiency criteria is satisfied.

Step A.16- Solve for (L_1):

L_1 = distance to first inlet

$$L_1 = \frac{43{,}560 Q_t}{C C_f i W_p} E \qquad \text{(Equation 1)}$$

E = 1.0 (no bypass flow to first inlet)

i = 2.28 inches per hour (assume 5-minute t_c using a 10-year storm design, Hydrologic Zone 8, using IDR curve in **Chapter 7**)

C_f = 1.0 (per Appendix F, Chapter 7)

$$L_1 = \frac{43{,}560(4.82)(1.0)}{0.9(1.0)(2.28)(46.5)} = 2{,}200 \text{ feet}$$

Step A.17- Calculate (L):

L = distance to successive inlets

$$L = \frac{43{,}560 Q_t E}{C C_f i W_p} \qquad \text{(Equation 1)}$$

E = 0.72 (distance to subsequent inlets should account for bypass flow)

$$L = \frac{43{,}560(4.82)(0.72)}{0.9(1.0)(2.28)(46.5)} = 1{,}584 \text{ feet}$$

Maximum inlet spacing shall be limited to 400 feet.
Therefore, L_1 = 2200 feet and L_2 = 400 feet

5.4.1.3 Method B

- T = allowable spread width = shoulder width + 2 feet
  = 10.5 feet + 2 feet
  = 12.5 feet (per Table A for highway on-grade section, less than 45 miles per hour)
- Assume inlet is 30 percent clogged (per Table A)

- W_g = 1.39 feet (grate width for CG-1 inlet 30 percent clogged per Table B, Appendix D.)
- L_g = 2.31 feet (grate length for CG-1 inlet 30 percent clogged per Table B, Appendix D)
- L_2 = 400 feet (maximum spacing between successive inlets per Appendix D)
- L_{ex} = 4.20 feet (curb opening extension length, 30 percent clogged, Table B, Appendix D)
- h_{ex} = 0.33 feet (curb opening height for curb opening extension 30 percent clogged, Table B, Appendix D)

Step B.1- Solve for (Q_t):

Q_t = total gutter flow (The approach gutter section to the inlet is used to calculate the total flow.)

$$Q_t = \frac{0.56}{n} S_x^{1.67} S_L^{0.5} T^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_t = \frac{0.56}{0.016}(0.02)^{1.67}(0.0125)^{0.5}(12.5)^{2.67} = 4.82 \text{ cubic feet per second}$$

Step B.2- Solve for (E_o):

E_o = ratio of flow in the depressed section to total gutter flow

$$E_o = 1 - \left(1 - \frac{W}{T}\right)^{2.67} = 1 - \left(1 - \frac{2}{12.5}\right)^{2.67} = 0.372 \quad \left[\begin{matrix}\text{Equation 4 or Chart 2,} \\ \text{Appendix H}\end{matrix}\right]$$

Step B.3- Solve for (S_e):

S_e = equivalent cross-slope (foot per foot)

$$S'_w = \frac{a}{W_d}$$

a = 1.5 inches (gutter depression per standard drawing RD 366)

W_d = 2 feet (width of the depressed gutter section)

$$S'_w = \frac{\left(\frac{1.5 \text{ in}}{12 \text{ in/ft}}\right)}{2 \text{ ft}} = 0.0625 \text{ foot per foot}$$

$$S_e = S_x + S'_W E_o$$ (Equation 12)

$$S_e = 0.02 + (0.0625)(0.372) = 0.0432$$

Step B.4- Solve for (L_T):

L_T = curb-opening length required to intercept 100 percent of gutter flow

$$L_T = 0.6Q_t^{0.42}S_L^{\ 0.3}\left(\frac{1}{nS_e}\right)^{0.6}$$ (S_e substituted for S_x in Equation 10)

$$L_T = 0.6(4.82)^{0.42}(0.0125)^{0.3}\left(\frac{1}{(0.016)(0.0432)}\right)^{0.6} = 24.5 \text{ feet}$$

Step B.5- Solve for (E):

E = efficiency of curb opening extension (curb opening adjacent to grate is ignored throughout this example)

$$E = 1 - \left(1 - \frac{L_{ex}}{L_T}\right)^{1.8}$$ (Equation 11 or Chart 7, Appendix H)

L_{ex} = length of curb-opening extension (reference standard drawing No. RD 366)

L_{ex} = 4.20 feet (curb opening extension length, 30 percent clogged, Table B, Appendix D)

$$E = 1 - \left(1 - \frac{4.2}{24.5}\right)^{1.8} = 0.29 = 29 \text{ percent}$$

Step B.6- Solve for (Q_{iex}):

Q_{iex} = flow intercepted by curb-opening extension

Q_{iex} = EQ_t = (0.29)(4.82) = 1.40 cubic feet per second

Step B.7- Solve for (Q_b):

Q_b = bypass flow from curb-opening extension and is total flow toward grate inlet

Q_b = $Q_t – Q_{iex}$
= 4.82 – 1.40 = 3.42 cubic feet per second

Step B.8- Solve for (T):

T = spread at grate (after interception by curb-opening extension)

This is done by trial and error. Start by assuming an initial value of T = 11.0 feet

T_s = T – W
= 11.0 – 2.0 = 9.0 feet

Q_s = $\frac{0.56}{n} S_x^{1.67} S^{0.5} T_s^{2.67}$ (**Chapter 8** or Chart 5, Appendix H)

Q_s = $\frac{0.56}{0.016}(0.02)^{1.67}(0.0125)^{0.5}(9.0)^{2.67}$ = 2.01 cubic feet per second

E_o = $1-\left(1-\frac{W}{T}\right)^{2.67} = 1-\left(1-\frac{2}{11.0}\right)^{2.67} = 0.415$ $\left[\begin{array}{r}\text{Equation 4 or Chart 2,}\\ \text{Appendix H}\end{array}\right]$

Q_t = $\frac{Q_s}{(1-E_o)} = \frac{2.01}{1-0.415} = 3.44$ cubic feet per second

Bypass flow from the curb opening extension is 3.42 cubic feet per second. Total flow toward the catch basin grate at a spread of 11.0 feet is 3.44 cubic feet per second. Therefore the spread at the catch basin grate is 11.0 feet.

Step B.9- Solve for (V):

V = average gutter flow velocity at grate in feet per second

V = $\frac{Q_t}{A} = \frac{2Q_t}{T_s^2 S_x}$ (**Chapter 8**)

V = $\frac{2\,(3.44)}{(11)^2\,(0.02)}$ = 2.84 feet per second

Step B.10- Solve for (R_f):

R_f = ratio of frontal flow intercepted to total frontal flow

R_f = $1 - 0.09\,(V - V_o)$ (Equation 6 or Chart 1, Appendix H)

V_o = gutter velocity where splash over first occurs (in feet per second)

L_g = 2.31 feet (CG-1 grate length, 30 percent clogged per Table B, Appendix D)

Grate type = P-1-$^7/_8$-4

Therefore from Chart 1 (Appendix H), V_o = 5.0 feet per second

R_f = 1 – 0.09 (2.84 – 5.0) = 1.19

R_f = cannot exceed 1.0, therefore

R_f = 1.0

Step B.11- Solve for (R_s):

R_s = ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\dfrac{0.15V^{1.8}}{S_x L^{2.3}}\right)}$$ (Equation 7 or Chart 4, Appendix H)

$$R_s = \frac{1}{1+\left(\dfrac{0.15\,(2.84)^{1.8}}{(0.02)(2.31)^{2.3}}\right)} = 0.12$$

Step B.12- Solve for (E_g):

E_g = interception efficiency of the inlet grate

$E_g = R_f E_o + R_s\,(1 – E_o)$ (Equation 8)

E_g = (1.0)(0.415) + 0.12 (1 – 0.415) = 0.49 = 49 percent

Step B.13- Solve for (Q_{ig}):

Q_{ig} = interception flow of grate inlet

$Q_{ig} = E_g Q_t$ = 0.49(3.42) = 1.68 cubic feet per second

Step B.14- Solve for (Q_i):

Q_i = total interception flow (both grate inlet and curb-opening extension)

Q_i = interception flow of curb-opening extension (Q_{iex}) + interception flow of grate inlet (Q_{ig})

$Q_i = Q_{iex} + Q_{ig}$

Q_i = 1.40 + 1.68 = 3.08 cubic feet per second

Step B.15- Solve for (E):

E = combination inlet efficiency

E = Q_i/Q_t

= 3.08/4.82 = 0.64 = 64 percent

Okay (70 percent minimum interception efficiency does not apply to Method B.)

Step B.16- Calculate (L_1):

L_1 = distance to first inlet

$$L_1 = \frac{43{,}560 Q_t E}{C C_f i W_p}$$ (Equation 1)

E = 1.0 (no bypass flow for first inlet)

i = 2.28 inches per hour (assume 5-minute t_c using a 10-year storm design, Hydrologic Zone 8, using IDR curve in **Chapter 7**)

C_f = 1.0 (per Chapter 7, Appendix F)

$$L_1 = \frac{43{,}560(4.82)}{0.9(1.0)(2.28)(46.5)}(1.0) = 2{,}200 \text{ feet}$$

Step B.17- Calculate (L):

L = distance to successive inlets

$$L = \frac{43{,}560Q_t}{CC_f iW_p}E \qquad \text{(Equation 1)}$$

E = 0.64 (distance to subsequent inlets should account for bypass flow)

$$L = \frac{43{,}560(4.82)}{0.9(1.0)(2.28)(46.5)}(0.64) = 1{,}408 \text{ feet}$$

Maximum inlet spacing shall be limited to 400 feet

Therefore L_1 = 2,200 feet and L_2 = 400 feet

5.5 Trench Drain System (On-grade)

Trench drain systems with its continuous grate configuration are best suited for intercepting flow on very flat surfaces with little or no longitudinal grade. They can be used on curbed or uncurbed sections and offer little interference to traffic operations. The primary advantage of using trench drains is their ability to intercept flow over a wide section. However, trench drains are susceptible to clogging from sediments and debris and are not recommended for use in environments where significant sediment or debris loads may be present.

Note: General information on trench drain systems is noted in Appendix C.

To aid in the design of trench drains, the designer should consider the following guidelines:

- The equations and figures used for the design of grate inlets (reference Section 5.1) should be used in the design of trench drains.
- Consider hydraulic conveyance capacity curves or data from a manufacturer.
- Consider hydraulic capacity curves or data for available grates from a manufacturer.
- Trench drain grate shall be bicycle safe and rated for heavy highway traffic.
- When using design Method B, the designer should assume 50 percent clogging which will result in providing twice the calculated required length for flow interception because trench drains tend to plug.
- The minimum cleanout velocity for trench drain systems should be 3 feet per second.
- Trench drains should not be used in areas with high traffic speeds greater than or equal to 45 miles per hour.

6.0 Inlets in Sag Location

Inlets in sag locations operate as weirs under low head conditions. When greater head conditions develop they function as an orifice. Flow may fluctuate between weir and orifice control depending on the grate size, the curb-opening height, or the slot width of the inlet. Flow is in a transition stage at depths between when weir flow definitely prevails and when orifice flow prevails. Control is ill-defined and flow may fluctuate between weir and orifice control at these depths.

The efficiency of inlets in sag locations is critical because all runoff which enters the sag must be passed through the inlet. Total or partial clogging of inlets in these locations can result in hazardous ponding conditions. Grate inlets alone are not recommended for use in sag locations because of the tendencies of grates to become clogged. Combination inlets or curb-opening inlets are recommended for use in these locations because of its better hydraulic capacity and debris handling capabilities.

Grate inlets can be used successfully in sag locations although curb-opening inlets are generally preferred. Grate inlets without a curb box (combination inlet) can be utilized at minor sag points where debris potential is limited. For example a minor sag point might be on a ramp as it joins a mainline. In sag locations where debris is likely, and a grate will be used, it is recommended to install a combination inlet (curb-opening and grate). When designing grates in sag locations, it is recommended to assume half the grate is clogged with debris (as noted in Table A).

It is good engineering practice to place a minimum of one flanking inlet on each side of the sag inlet in locations such as underpasses and in sag vertical curves in depressed sections where significant ponding can occur. The flanking inlets should be placed so they will limit spread on low gradient approaches to the low point and act in relief of the sag inlet if it should become clogged or if the allowable spread is exceeded. Further discussion and methodology of flanking inlets are presented in Section 6.6.

Note:

- *If ponding depths exceed the curb height the designer should verify adjacent properties will suffer no flood damage.*
- *The maximum spread width in the sag shall be limited as noted in Table A.*
- *The design discharge shall be the 25-year or 50-year bypass flow (reference Table A) from the first upstream inlet on each side of the sag plus the runoff from any additional areas draining to the sag.*

6.1 Grate Inlets (Sag)

A grate inlet in a sag operates as a weir up to a depth of about 4.5 inches and as an orifice for depths greater than 17 inches. A transition from weir to orifice flow occurs between these depths. Chart 8 (Appendix H) is a plot of Equation 13 and Equation 14 for various grate sizes. The effect of grate size on the depth at which a grate operates as an orifice is apparent from the figure. Transition from weir to orifice flow results in interception capacity less than that computed by either weir or the orifice equations. This capacity can be approximated by drawing in a curve between the lines representing the perimeter and net area of the grate to be used.

The capacity of a grate inlet operating as a weir is:

$$Q_i = C_w P d^{1.5} \qquad \text{(Equation 13)}$$

Where:

Q_i = grate inlet capacity (cubic feet per second)
P = perimeter of grate excluding bar widths and side against curb in feet
d = depth of water at curb measured from the normal cross slope gutter flow line in feet
C_w = 3.0

The capacity of a grate inlet operating as an orifice is:

$$Q_i = CA\,(2gd)^{0.5} \qquad \text{(Equation 14)}$$

Where:

Q_i = grate inlet capacity (cubic feet per second)
C = 0.67 (orifice coefficient)
A = clear opening area of the grate in square feet
g = 32.2 feet per second squared

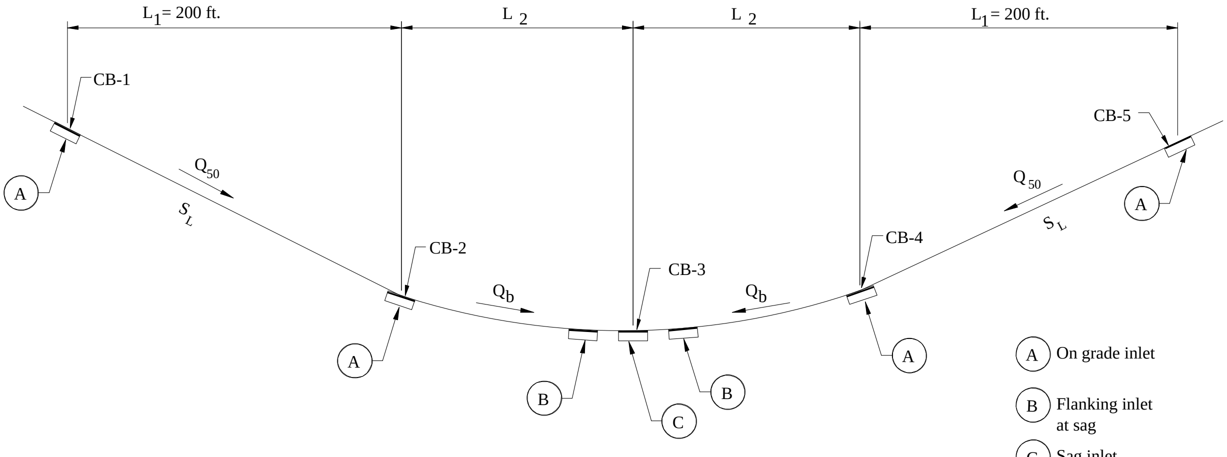
Note: Standard grate inlets used in ODOT storm drainage systems are noted in Appendix C.

6.1.1 Grate Inlet (Sag) Example

The following example illustrates the design of grate inlets in a sag.

6.1.1.1 Determine the appropriate inlet spacing in a sag

Sketch:



GRATE INLETS
NTS

Given:

- Inlet design Method B (Appendix D)
  Note: Method A or B could be used. Method selected should be used for entire design.
- Highway section, main line sag point (greater than or equal to 45 miles per hour)
- Standard Curb (reference **Chapter 8**)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- S_L = 0.035 foot per foot (roadway longitudinal slope)
- W_P = 46.5 feet (width of contributing drainage area, 2 – 12-foot lanes with 10.5-foot shoulder/gutter, 5-foot sidewalk, 7-foot median)
- S_x = 0.02 foot per foot (shoulder and roadway cross slope)
- Flanking inlets ignored in calculations
- 50-year design, Hydrologic Zone 8 (IDR curves located in **Chapter 7**)
- G-2 inlets
- For on grade inlets(CB-1, CB-2, CB-4, and CB-5) assume 30 percent clogging
  - W_G = 1.84 feet (G-2 grate width, 30 percent clogged, Table B, Appendix D)
  - L_G = 2.26 feet (G-2 grate length, 30 percent clogged, Table B, Appendix D)
  - P = 5.94 feet (G-2 grate perimeter next to curb, 30 percent clogged, Table B, Appendix D)
- For low point (sag) inlets (CB-3) assume 50 percent clogging
  - W_G = 1.53 feet (G-2 grate width, 50 percent clogged, Table C, Appendix D)
  - L_G = 1.95 feet (G-2 grate length, 50 percent clogged, Table C, Appendix D)
  - P = 5.0 feet (G-2 grate perimeter next to curb, 50 percent clogged, Table C, Appendix D)
- L_1 = 200 feet
- T = shoulder width = 10.5 feet

Criteria:

- Maximum pond width = allowable spread width
- Allowable spread width is 0 feet into the outside lane (reference Table A, Appendix D)
- For on-grade inlets assume a 30 percent clogging factor because Method B has been selected to solve the example problem.
- For low point inlet in a main line sag, assume a 50 percent clogging factor because Method B has been selected to solve the example problem

Solution:

Step B.1- Solve for (d_1):

d_1 = low point flow depth at curb (at allowable spread width)

$d_1 = TS_x$ (**Chapter 8**)

$d_1 = (10.5)0.02 = 0.21$ feet

$d_1 = 0.21$ feet = 2.52 inches

From Section 6.1, d equals 2.52 inches which is less than 4.5 inches; therefore sag inlet operates as a weir.

Step B.2- Solve for (Q_i):

Q_i = low point grate inlet (CB-3) capacity at maximum allowable spread

Q_i = $C_w P d_1^{1.5}$ (Equation 13)

d_1 = 0.21 feet

P = 5.0 feet (G-2 grate perimeter next to curb, 50 percent clogged, Table B, Appendix D)

Q_i = $3.0(5.0)(0.21)^{1.5}$ = 1.44 cubic feet per second

StepB.3- Solve for (Q_{50}):

Q_{50} = 50-year peak flow (cubic feet per second) draining toward catch basins CB-2 and CB-4

Q_{50} = CiA
C = 0.9 (runoff coefficient for pavement)
i = 3.0 inches per hour (50-year rainfall intensity, IDR curves located in **Chapter 7**)

A = W_P L

= (46.5 feet)(200 feet) = 9,300 square feet

= 0.21 acre

Q_{50} = (0.9)(3.0)(0.21) = 0.57 cubic feet per second

Therefore, 0.57 cubic feet per second drains toward catch basins CB-2 and CB-4.

Step B.4- Solve for (T):

T = total spread of water in feet just upstream of inlets CB-2 and CB-4

$$Q = \frac{0.56}{n} S_X^{1.67} S_L^{0.5} T^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

Use Chart 5 (Appendix H) or rearrange the above equation to solve for T.

$$T = \left[\frac{Qn}{0.56 S_L^{0.5} S_x^{1.67}}\right]^{0.375} = \left[\frac{(0.57)(0.016)}{0.56(0.035)^{0.5}(0.02)^{1.67}}\right]^{0.375}$$

T = 4.6 feet (spread just upstream of inlets CB-2 and CB-4)

Okay because this is less than the allowable spread of 10.5 feet.

Step B.5- Solve for (V):

V = average gutter flow velocity (in feet per second)

$$V = \frac{Q_t}{A} = \frac{2Q_t}{T^2 S_x} = \frac{2(0.57)}{(4.6)^2(0.02)} = 2.65 \text{ feet per second}$$ (**Chapter 8**)

Step B.6- Solve for (E_o):

E_o = ratio of frontal flow to total flow

E_o = $$1-\left(1-\frac{W_g}{T}\right)^{2.67}$$ (Equation 4 or Chart 2, Appendix H)

W_g = 1.84 feet (G-2 grate width, 30 percent clogged, Table B, Appendix D)

E_o = $$1-\left(1-\frac{1.84}{4.6}\right)^{2.67}$$

E_o = 0. 74 = 74 percent

Step B.7- Solve for (R_f):

R_f = ratio of frontal flow intercepted to total frontal flow

R_f = $1 – 0.09 (V – V_o)$ (Equation 6 or Chart 1, Appendix H)

V = average flow velocity in the gutter (in feet per second)

V_o = gutter velocity where splash over first occurs (in feet per second)

V = 2.65 feet per second

L_g = 2.26 feet (G-2 grate length, 30 percent clogged, Table B,)

V_o = 5.1 feet per second (per Chart 1, Appendix H)

Grate type = P – $1^7/_8$ – 4

R_f = 1 – 0.09 (2.65 – 5.1)

R_f = 1.22

R_f can not exceed 1.0, therefore,

R_f = 1.0

Step B.8- Solve for (R_s):

R_s = ratio of side flow intercepted to total side flow

R_s = $$\frac{1}{1+\left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)}$$ (Equation 7 or Chart 4, Appendix H)

V = 2.65 feet per second

L = 2.26 feet (G-2 grate length, 30 percent clogged, Table B, Appendix D)

R_s = $$\frac{1}{1+\left(\frac{0.15\,(2.65)^{1.8}}{(0.02)(2.26)^{2.3}}\right)}$$

R_s = 0.131

Step B.9- Solve for (E):

E = inlet interception efficiency

$E = R_f E_o + R_s (1 - E_o)$ (Equation 8)

$E = (1.0)(0.74) + 0.131 (1 - 0.74) = 0.77$ Okay

Note: When using Method A, E must be equal to or greater than 0.70.

Step B.10- Solve for (Q_b):

Q_b = bypass flow from adjacent catch basins

$Q_b = Q - Q_i$

$Q_i = EQ = (0.77)(0.57) = 0.44$

$Q_b = 0.57 - 0.44 = 0.13$ cubic feet per second

Step B.11- Calculate (L_2):

L_2 = distance between sag inlet CB-3 and CB-2, and distance between sag inlet CB-3 and CB-4

$$L_2 = \frac{43{,}560Q}{CC_f iW_p}E \qquad \text{(Equation 1)}$$

Equation 1 is modified to calculate L_2 in sags, therefore

$$L_2 = \frac{43{,}560(Q_i - 2Q_b)}{iCC_f 2W_p}$$

i = 3.0 inches per hour (assume 5-minute t_c using a 50-year storm design, Hydrologic Zone 8, use IDR curve in **Chapter 7**)

$C = 0.90$

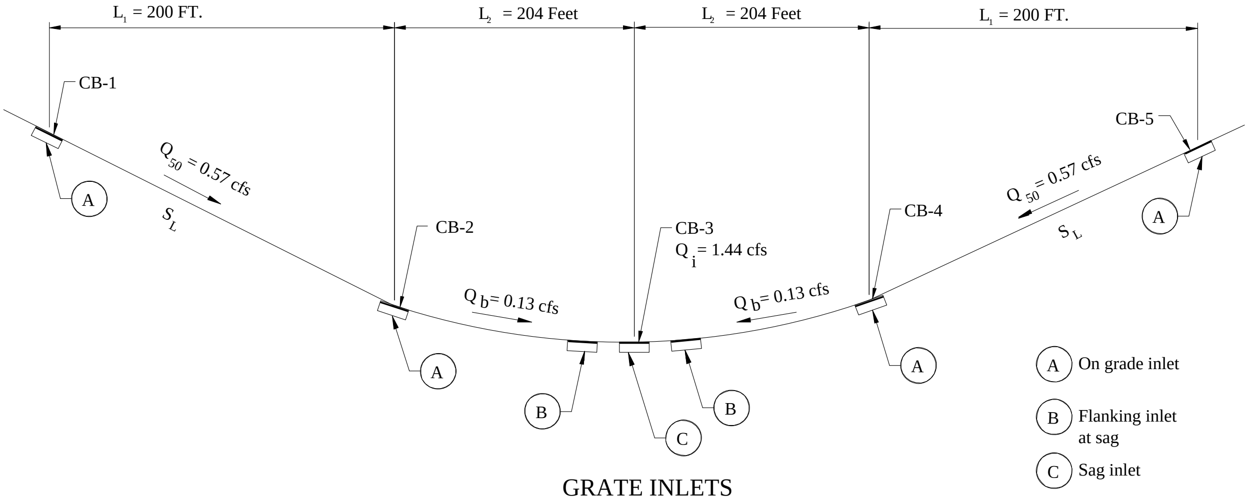
C_f = 1.0 (per **Chapter 7**, Appendix F)

W_p = 46.5 feet

Q_i = 1.44 cubic feet per second (low point inlet (CB-3) interception capacity)

$$L_2 = \frac{43{,}560[1.44 - 2(0.13)]}{(0.9)(1.0)(3.0)(2)(46.5)} = 204 \text{ feet}$$

Maximum distance between inlets is 204 feet.



GRATE INLETS

NTS

6.2 Curb-Opening Inlets (Sag)

The capacity of a curb-opening inlet in a sag depends on water depth at the curb, the curb-opening length, and the height of the curb-opening (see the horizontal throat figure below). The inlet operates as a weir to depths equal to the curb-opening height and as an orifice at depths greater than 1.4 times the opening height. At depths between 1.0 and 1.4 times the opening height, flow is in a transition stage.

Note: Standard curb-opening inlets used in ODOT storm drainage systems are noted in Appendix C

The equation for the interception capacity of a depressed curb-opening inlet operating as a weir is:

$$Q_i = 2.3 (L + 1.8 W)d^{1.5} \quad \text{(Equation 15)}$$

Where:

L = length of curb-opening in feet

W = width of depression in feet

d = depth of water at curb measured from the normal cross slope gutter flow line in feet

See Chart 9 (Appendix H) for a definition sketch.

The weir equation for curb-opening inlets without depression becomes:

$$Q_i = 3 L d^{1.5} \quad \text{(Equation 16)}$$

The depth limitation for operation as a weir becomes: d less than h (h = height of curb-opening inlet in feet)

Chart 10, Appendix H should be used for designing undepressed Curb-Opening Inlet Capacity in Sump Locations.

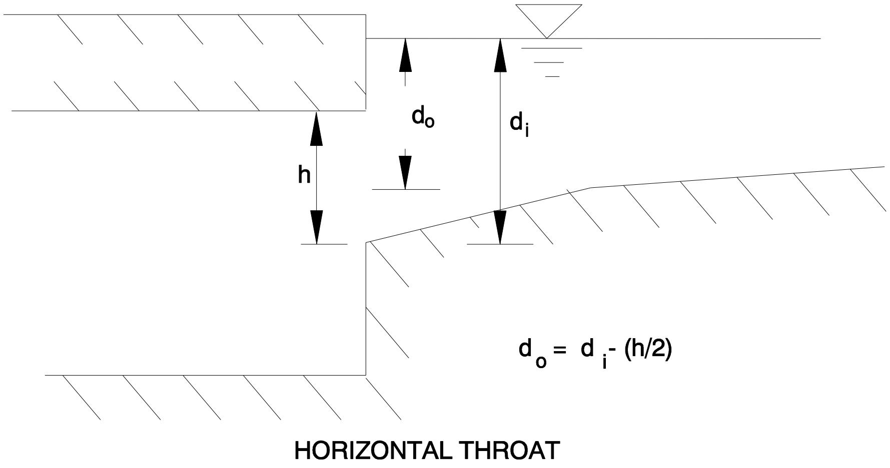
Curb-opening inlets operate as orifices at depths greater than approximately 1.4 times the opening height. The interception capacity can be computed by:

$$Q_i = C_o A \left[2g \left(d_i - \frac{h}{2} \right) \right]^{0.5} \quad \text{(Equation 17)}$$

Where:

C_o = orifice coefficient (0.67)
h = height of curb-opening orifice in feet (figure below)
d_i = depth at lip of curb-opening in feet (figure below)

Note: Equation 17 is applicable to depressed and undepressed curb-opening inlets and the depth at the inlet includes any gutter depression.



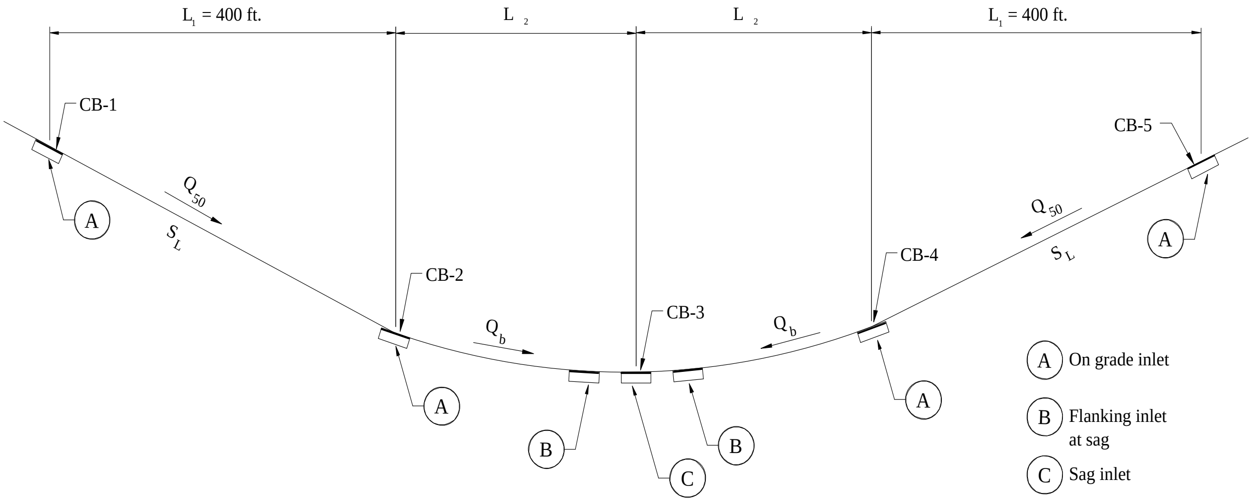
Curb-Opening Inlet

6.2.1 Curb-Opening Inlet (Sag) Example

The following example illustrates the design of curb-opening inlets in a sag.

6.2.1.1 Determine inlet spacing in a sag location

Sketch:



CURB OPENINGS

NTS

Given:

- Inlet design method = B (Appendix D)
  Note: Method A or B could be used. Method selected should be used for the entire design.
- Standard Curb (reference Chapter 8)
- Highway-main line sag, less than 45 miles per hour (per Table A, Appendix D)
- S_L = 0.0025 foot per foot (roadway longitudinal slope)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- W_p = 36 feet (width of contributing area, 2 – 12-foot lanes with 7-foot shoulder, 5-foot sidewalk)
- S_x = 0.02 foot per foot (roadway cross slope)
- CG-3 inlets
- 50-year design (per Table A), Salem area (Hydrologic Zone 7)
- L_c = 1.25 feet (length of curb opening, reference Table C, 50 percent clogged)
- L_c = 1.75 feet (length of curb opening, reference Table B, 30 percent clogged)
- a = 2 inches (inlet depression)
- W_d = 2.0 feet (width of depressed gutter section at inlet only)
- h_c = 0.36 feet (curb opening height, reference Table B and C)
- L_1 = 400 feet
- Flanking inlets ignored in calculations

Criteria:

- For on-grade inlets, assume a 30 percent clogging factor because Method B has been selected to solve the example problem.
- For low point inlet in a mainline sag use a 50 percent clogging factor because Method B has been selected to solve the example problem (see Tables A and C, Appendix D)
- T = shoulder width + 2 feet = 7 feet + 2 feet = 9 feet (allowable spread width, see Table A, Appendix D)

Solution: Solve inlet design using Method B

Step B.1 Solve for (d_1):

d_1 = low point flow depth at curb (at allowable spread)

d_1 = $TS_x + a$ (**Chapter 8**)

= $9(0.02) + 2/12 = 0.35$ feet = 4.16 inches

Because flow depth (0.35 feet) is less than curb opening height (0.36 feet) inlet CB-3 operates as a weir.

Step B.2- Solve for (Q_i):

Q_i = interception flow of low point curb-opening inlet CB-3

Q_i = $2.3(L+1.8W)d^{1.5}$ (Equation 15)

(Equation 15 is for depressed curb-opening inlets operating as a weir.)

L = 1.25 feet (length of curb opening, 50 percent clogged)

W = 2 feet (width of depression)

Q_i = $2.3[1.25 + 1.8(2)](0.35)^{1.5}$ = 2.31 cubic feet per second

(maximum allowable flow to low point inlet CB-3)

Step B.3- Solve for (Q_{50}):

Q_{50} = 50-year peak flow (cubic feet per second) draining toward catch basins CB-2 and CB-4

Q_{50} = CiA (**Chapter 7**)

C = 0.9 (runoff coefficient for pavement)

i = 2.8 inches per hour (50-year rainfall intensity, IDR curves located in **Chapter 7**)

A = WL

= (36 feet)(400 feet) 14,400 square feet

= 0.33 acre

Q_{50} = (0.9)(2.8)(0.33) = 0.83 cubic feet per second

Therefore, 0.83 cubic feet per second drains toward catch basins CB-2 and CB-4.

Step B.4- Solve for (T):

T = total spread of water in feet just upstream of inlets CB-2 and CB-4

$$Q = \frac{0.56}{n} S_X^{1.67} S_L^{0.5} T^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

Use Chart 5 (Appendix H) or rearrange the above equation to solve for T.

$$T = \left[\frac{Qn}{0.56 S_L^{0.5} S_x^{1.67}}\right]^{0.375} = \left[\frac{(0.83)(0.016)}{0.56(0.0025)^{0.5}(0.02)^{1.67}}\right]^{0.375}$$

T = 8.75 feet (spread just upstream of catch basins CB-2 and CB-4)

Okay (because this is less than the allowable spread of 9 feet)

Step B.5- Calculate (E_o):

E_o = ratio of flow in the depressed section to total gutter flow

$$E_o = 1 - \left(1 - \frac{W_d}{T}\right)^{2.67}$$ (Equation 4 or Chart 2, Appendix H)

$$E_o = 1 - \left(1 - \frac{2}{8.75}\right)^{2.67}$$

= 0.50 = 50 percent

Step B.6- Calculate (S_e):

S_e = equivalent cross slope (foot per foot)

$S_e = S_x + S'_w E_o$ (Equation 12)

S_x = roadway Cross Slope

$S'_w = \frac{a}{W}$ (cross slope of the gutter measured from the cross slope of the pavement, S_x)

$$= \frac{a}{W} = \frac{(2/12)}{2} = 0.0833 \text{ foot per foot}$$

S_e = 0.02 + (0.083)(0.50) = 0.0615

Step B.7- Calculate (L_T):

L_T = curb opening length required to intercept 100 percent of the flow

$$L_T = 0.6\, Q_t^{0.42}\, S_L^{0.3} \left(\frac{1}{n\, S_e}\right)^{0.6}$$ (S_e is substituted for S_x in Equation 10)

L_T = $0.6\,(0.83)^{0.42}\,(0.0025)^{0.3}\left(\dfrac{1}{(0.016)(0.0615)}\right)^{0.6}$

L_T = 5.86 feet

Step B.8- Solve for (E):

E = curb opening efficiency

L_c = 1.75 feet (length of curb opening 30 percent clogged)

$$E = 1-\left[1-\frac{L_c}{L_T}\right]^{1.8} = 1-\left[1-\frac{1.75}{5.86}\right]^{1.8} \quad \text{(Equation 11 or Chart 7, Appendix H)}$$

E = 0.47

Okay (70 percent minimum efficiency criteria does not apply to Method B)

Step B.9- Solve for (Q_b):

Q_b = flow that is not intercepted by an inlet and must be included in the evaluation of downstream gutter and inlet (cubic feet per second)

Q_b = $Q - Q_i$

Q_i = EQ = (0.47)(0.83) = 0.39 cubic feet per second

Q_b = 0.83 – 0.39 = 0.44 cubic feet per second

Step B.10- Solve for (L_2):

L_2 = distance between sag inlet CB-3 and CB-2, and

= distance between sag inlet CB-3 and CB-4

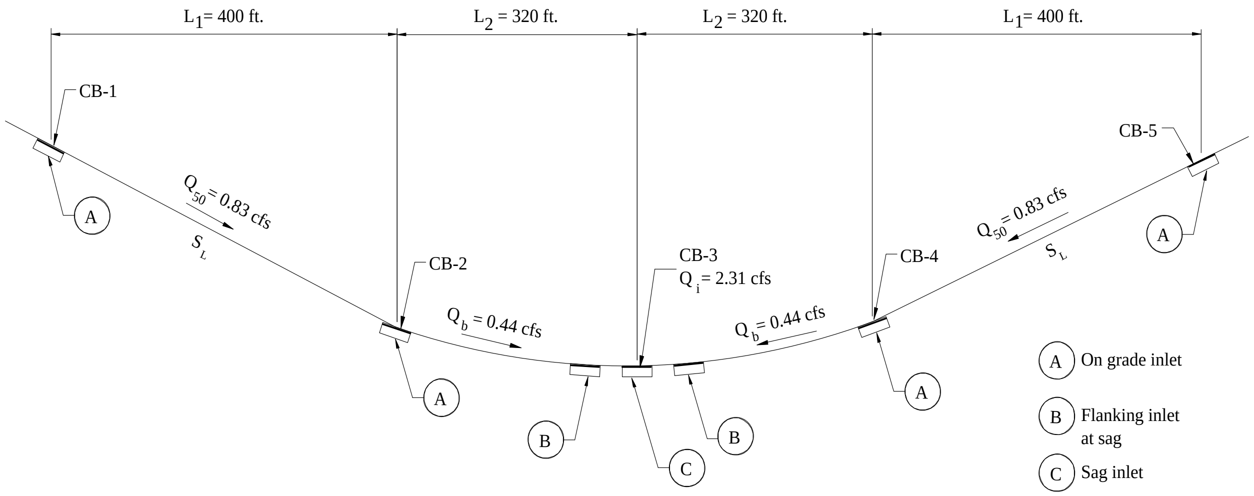
$$L_2 = \frac{43{,}560Q}{CC_f\,iW_p}E \quad \text{(Equation 1)}$$

Equation 1 is modified to calculate L_2 in sags, therefore

$$L_2 = \frac{43{,}560(Q_i - 2Q_b)}{iCC_f\,2W_p}$$

Q_i = 2.31 cubic feet per second (low point inlet (CB-3) interception capacity)

$$L_2 = \frac{43{,}560[2.31 - 2(0.44)]}{(0.9)(1.0)(3.0)(2)(36.0)} = 320\text{ feet}$$



CURB OPENINGS

NTS

6.3 Slotted Inlets (Sag)

The use of slotted drain inlets in sag configurations is generally discouraged because of the tendency of such inlets in sags to intercept debris and clog. However, there may be locations where it is desirable to supplement an existing low point inlet with the use of a slotted drain. It is not recommended to place slotted drain inlets in sags unless a tapered slot is provided.

Note:

- *Standard slotted inlets used in ODOT storm drain systems are noted in Appendix C.*
- *When using inlet design Method B, the designer should assume 50 percent clogging which will result in providing twice the calculated required length for flow interception because slotted inlets tend to plug.*
- *A tapered slot inlet has a sloped invert to provide positive drainage. This is necessary in applications when the finished grade slot elevation is constant.*

Slotted inlets in sag locations perform as weirs to depths of about 0.2 feet (2.4 inches). This condition is dependent on slot width and length. Slotted inlets perform as orifices at depths greater than about 0.4 feet (4.8 inches). Flow is in a transition stage between these depths.

The interception capacity of a slotted inlet operating as a weir can be computed by the following equation:

$$Q_i = 2.48 L d^{1.5} \qquad \text{(Equation 18)}$$

Where:

L = length of slot in feet
d = depth of water at slot in feet

The interception capacity of a slotted inlet operating as an orifice can be computed by the following equation:

$$Q_i = 0.8\ L\ W\ (2gd)^{0.5} \qquad \text{(Equation 19)}$$

Where:

W = width of slot in feet
L = length of slot in feet
d = depth of water at slot in feet
g = 32.2 feet per second squared

For a slot width of 1.75 inches, Equation 19 simplifies to:

$$Q_i = 0.94\ L\ d^{0.5} \qquad \text{(Equation 20)}$$

The orifice equation noted in this section to compute the interception capacity of slotted inlets should be used at depths between 2.4 inches and 4.8 inches. The orifice coefficient varies with depth, slot width, and the length of the slotted inlet. Chart 11, Appendix H, provides solutions for weir flow and a plot representing data at depths between weir and orifice flow.

6.4 Combination Inlets (Sag)

Combination inlets consist of a grate and curb-opening. These types of inlets are recommended for use in sags because of their better hydraulic capacity and debris handling capabilities. The two combination inlets commonly used in storm drainage design are equal length inlets and sweeper inlets.

Equal length inlets refer to a grate inlet placed along side a curb-opening inlet and both have the same length. Standard ODOT inlets CG-1 and CG-2 are equal length inlets as noted in Appendix C. The interception capacity of these types of inlets is essentially equal to that of a grate only inlet in weir flow. The capacity of equal length combination inlets in orifice flow is equal to the capacity of the grate plus the capacity of the curb-opening.

A sweeper inlet refers to a grate inlet placed at the downstream end of a curb-opening extension. Standard ODOT inlets CG-1 and CG-2 can be modified to include a curb-opening extension as noted in Appendix C. The curb-opening in a sweeper inlet is longer than the grate and intercepts gutter flow before the flow reaches the grate. This type of inlet is more efficient than the equal length combination inlet and the curb-opening has the ability to intercept any debris which may clog the grate inlet.

Equation 13 and Chart 8, Appendix H, can be used for weir flow in combination inlets in sag locations. Assuming complete clogging of the grate, Equation 15, Equation 16, Equation 17 and Charts 9 and 10 (Appendix H) for curb-opening inlets are applicable.

Where depth at the curb is such that orifice flow occurs, the interception capacity of the inlet is computed by adding Equation 14 and Equation 17 as follows:

$$Q_i = 0.67\ A_g\ (2\ g\ d)^{0.5} + 0.67\ h\ L\ (2g\ d_o)^{0.5} \qquad \text{(Equation 21)}$$

Where:

A_g = clear area of the grate in square feet

g = 32.2 feet per second squared

d = depth at the curb in feet

h = height of curb-opening orifice in feet (reference the horizontal throat figure in Section 6.2)

L = length of curb-opening in feet

d_o = effective depth at the center of the curb-opening orifice in feet (reference the horizontal throat figure in Section 6.2)

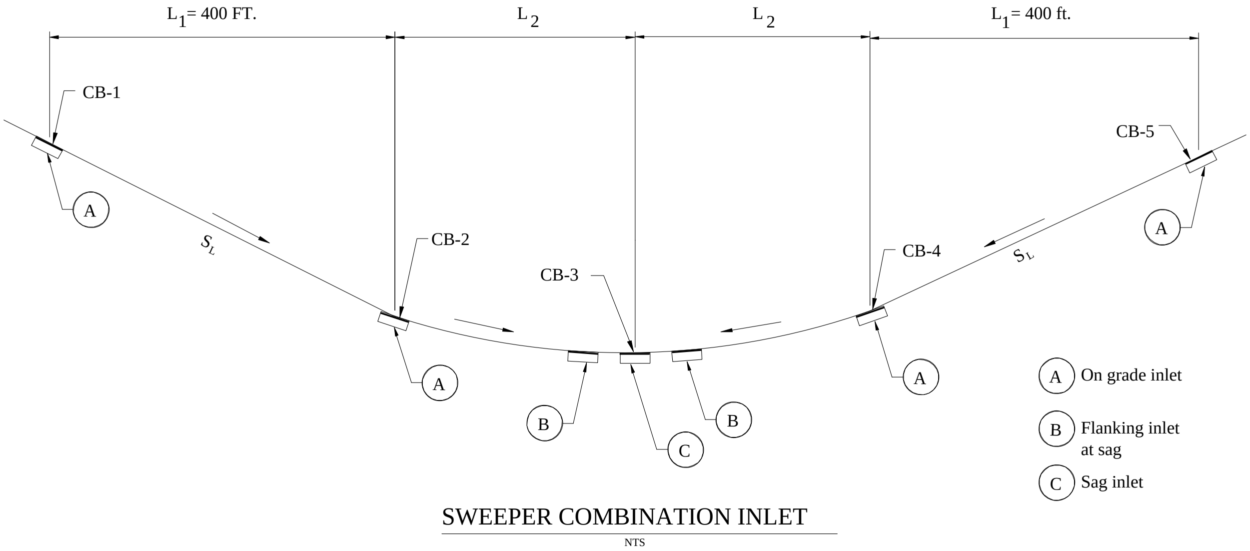
Trial and error solutions are necessary for determining the depth at the curb for a given flow rate using Chart 8, Chart 9, and Chart 10 (Appendix H) for orifice flow. Different assumptions for clogging of the grate can also be examined using these charts.

6.4.1 Sweeper Combination Inlet (Sag) Example

The following example illustrated the design of combination inlets in a sag.

6.4.1.1 Determine the appropriate inlet spacing in a sag.

Sketch:



Given:

- Inlet design method = B (Appendix D)
  Note: Method A or B could be used. Method selected should be used for the entire design.
- Highway main line sag (less than 45 miles per hour)

- Standard Curb (reference **Chapter 8**)
- W_p = 75.5 feet (width of contributing drainage area, 4-12-foot lanes with 10.5-foot shoulder, 5-foot sidewalk, 12-foot median)
- W = 2 feet (width of depressed section, at inlet only)
- S_L = 0.018 (roadway longitudinal slope)
- S_x = 0.02 (shoulder and roadway cross slope)
- CG-1 inlets width P-$1^7/_8$-4 grate (reference Table B, Appendix C)
- L_{ex} = 4.20 feet (curb opening extension 30 percent clogged, Table B, Appendix D)
- L_{ex} = 3.0 feet (curb opening extension 50 percent clogged, Table C, Appendix D)
- h_{ex} = 0.33 feet (curb opening height for curb opening extension)
- a = 1.5 inches (inlet depression)
- n = 0.016 (Manning's coefficient for asphalt pavement)
- L_1 = 400 feet
- Flanking inlets ignored in calculations
- 50-year design, Hydrologic Zone 8 (IDR curves in **Chapter 7**)
- W_g = 1.39 feet (CG-1 grate width, 30 percent clogged, per Table B, Appendix D)
- L_g = 2.31 feet (CG-1 grate length, 30 percent clogged, per Table B, Appendix D)
- P_g = 5.10 feet (CG-1 grate perimeter, 30 percent clogged, per Table B, Appendix D)
- W_g = 1.13 feet (CG-1 grate width, 50 percent clogged, per Table C, Appendix D)
- L_g = 2.05 feet (CG-1 grate length, 50 percent clogged, per Table C, Appendix D)
- P_g = 4.31 feet (CG-1 grate perimeter, 50 percent clogged, per Table C, Appendix D)

Criteria:

- For on-grade inlets, assume a 30 percent clogging factor because Method B has been selected to solve the example problem.
- For low point inlet in a main line sag, assume a 50 percent clogging factor because Method B has been selected.
- T = shoulder width + 2 feet
  = 10.5 feet + 2 feet
  = 12.5 feet (allowable flow spread per Table A, Appendix D)

Solution:

Step B.1- Solve for (d_1):

d_1 = low point flow depth at curb (at allowable spread width)

$d_1 = (T\text{-}W)S_x + WS_w$ (**Chapter 8**)

$d_1 = (12.5 – 2)(0.2) + (2)[(1.5/12)/2]$

$= 0.21 + 0.125$ feet

$d_1 = 0.335$ feet = 4.02 inches

Because flow depth (0.34 feet) is approximately equal to the curb opening height and not greater than 4.5 inches (Section 6.1), assume inlet operates as a weir.

Step B.2- Solve for (Q_i):

Q_i = low point grate inlet (CB-3) and curb opening extension capacity at maximum allowable spread

Q_{ig} = grate inlet capacity at maximum allowable spread

= $C_w P d^{1.5}$ (Equation 13)

P = 4.31 feet (CG-1 grate perimeter, 50 percent clogged, Table B, Appendix D)

d = 0.335 feet

Q_{ig} = $3.0(4.31)(0.335)^{1.5}$ = 2.51 cubic feet per second

Q_{iex} = low point curb opening extension (CB-3) capacity at maximum allowable spread

= $2.3(L + 1.8W)d^{1.5}$ (Equation 15)

L = 3.0 feet (curb opening extension 50 percent clogged, Table B, Appendix D)

W = 2 feet (width of depression)

d = 0.335 feet

Q_{iex} = $2.3\ [3.18 + 1.8(2)]\ (0.335)^{1.5}$

= 2.94 cubic feet per second

Q_i = $Q_{ig} + Q_{iex}$

= 2.51 + 2.94 = 5.45 cubic feet per second

Step B.3- Solve for (Q_{50}):

Q_{50} = 50-year peak flow (cubic feet per second) draining toward catch basins CB-2 and CB-4

Q = CiA (**Chapter 7**)

i = 3.0 inches/hour (IDR curves in **Chapter 7**)

C = 0.9

A = W_p L

= (75.5)(400) = 30,200 square feet = 0.70 acres

Q_{50} = (0.9)(3.0)(0.70) = 1.90 cubic feet per second

Therefore, 1.90 cubic feet per second drains toward catch basins CB-2 and CB-4.

Step B.4- Solve for (T):

T = total spread of water in feet just upstream of inlets CB-2 and CB-4

$$Q_{50} = \frac{0.56}{n} S_x^{1.67} S_L^{0.5} T^{2.67}$$

Use Chart 5 (Appendix H) or rearrange the previous equation to solve for T.

T = $\left(\frac{nQ_{50}}{0.56(S_x)^{1.67}(S_L)^{0.5}}\right)^{0.375}$ (**Chapter 8** or Chart 5, Appendix H)

T = $\left(\frac{0.016(1.90)}{0.56(0.02)^{1.67}(0.018)^{0.5}}\right)^{0.375} = 8.25\,\text{feet}$

Okay (because this is less than the allowable spread of 12.5 feet)

Step B.5- Solve for (E_o):

E_o = ratio of flow in the depressed section to total gutter flow

E_o = $1 - \left[1 - \frac{W}{T}\right]^{2.67}$ (Equation 4 or Chart 2, Appendix H)

E_o = $1 - \left[1 - \frac{2}{8.25}\right]^{2.67}$

E_o = 0.52

Step B.6- Solve for (S_e):

S_e = equivalent cross slope (foot per foot)

S_e = $S_x + S'_w E_o$ (Equation 12)

Where:

S'_w = $\frac{a}{W}$

a = 1.5 inches (inlet depression)

W = 2 feet (width of depression)

S'_w = $\frac{a}{W} = \frac{1.5/12}{2} = 0.0625$ foot per foot

S_e = $0.02 + 0.0625(0.52) = 0.0525$ foot per foot

Step B.7- Solve for (L_T):

L_T = curb-opening length required to intercept 100 percent of gutter flow

L_T = $0.6\,Q_t^{0.42}\,S_L^{0.3}\left(\frac{1}{n\,S_e}\right)^{0.6}$ [S_e is substituted for S_x in Equation 10 or Chart 6, Appendix H]

L_T = $0.6(1.9)^{0.42}(0.018)^{0.3}\left(\frac{1}{(0.016)(0.0525)}\right)^{0.6}$

L_T = 16.5 feet

Step B.8- Solve for (E):

E = curb-opening extension efficiency (neglect curb opening adjacent to grate)

$$E = 1-\left(1-\frac{L_{ex}}{L_T}\right)^{1.8}$$ (Equation 11 or Chart 7, Appendix H)

L_{ex} = length of curb-opening extension prior to grate inlet, 30 percent clogged

L_{ex} = 4.2 feet

$$E = 1\text{-}\left(1\text{-}\frac{4.2}{16.5}\right)^{1.8} = 0.41 = 41\text{percent}$$

Step B.9- Solve for (Q_{iex}):

Q_{iex} = flow intercepted by curb-opening extension

Q_{iex} = EQ_{50} = (0.41)(1.9) = 0.78 cubic feet per second

Step B.10- Solve for (Q_b):

Q_b = bypass flow from curb-opening extension and total flow toward grate inlet

Q_b = $Q_{50} - Q_{iex}$ = 1.90 – 0.78 = 1.12 cubic feet per second

Step B.11- Solve for (T):

T = total spread at grate (after interception by curb-opening extension)

This is done by trial and error. Start by assuming an initial value of T = 6.75 feet

T_s = T – W = 6.75 – 2.0 = 4.75 feet

$$Q_s = \frac{0.56}{n} S_x^{1.67} S_L^{0.5} T_s^{2.67}$$ (**Chapter 8** or Chart 5, Appendix H)

$$Q_s = \frac{0.56}{0.016}(0.02)^{1.67}(0.018)^{0.5}(4.75)^{2.67} = 0.44 \text{ cubic feet per second}$$

$$E_o = 1-\left[1-\frac{W}{T}\right]^{2.67} = 1-\left[1-\frac{2}{6.75}\right]^{2.67}$$ (Equation 4 or Chart 2, Appendix H)

E_o = 0.61

$$Q_t = \frac{Q_s}{1-E_o} = \frac{0.44}{1-0.61} = 1.13 \text{ cubic feet per second}$$

Bypass flow from curb opening extension is 1.13 cubic feet per second. Total flow toward the catch basin grate at a spread of 6.75 feet is 1.13 cubic feet per second. Therefore, the spread at the catch basin grate is 6.75 feet.

Step B.12- Solve for (V):

V = average gutter flow velocity at grate

$$V = \frac{Q_t}{A} = \frac{2Q_t}{T^2 S_x}$$ (**Chapter 8**)

$$V = \frac{2\,(1.13)}{6.75^2\,(0.02)} = 2.48 \text{ feet per second}$$

Step B.13- Solve for (R_f)

R_f = ratio of frontal flow intercepted to total frontal flow

R_f = $1 - 0.09\,(V - V_o)$ (Equation 6 or Chart 1, Appendix H)

V_o = gutter velocity where splash over first occurs (in feet per second)

CG-1 grate length = 2.31 feet (30 percent clogged, Table B)

Grate type = P-1-$^7/_8$-4

Therefore from Chart 1 (Appendix H), V_o = 5.0 feet per second

R_f = $1 - 0.09\,(2.48 - 5.0) = 1.23$

R_f cannot exceed 1.0, therefore

R_f = 1.0

Step B.14- Solve for (R_s)

R_s = ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1 + \left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)}$$ (Equation 7 or Chart 4, Appendix H)

V = 2.48 feet per second

L = 2.31 (CG-1 length, 30 percent clogged, Table B, Appendix D)

$$R_s = \frac{1}{1 + \left(\frac{0.15\,(2.48)^{1.8}}{0.02(2.31)^{2.3}}\right)} = 0.15$$

Step B.15- Solve for (E_g):

E_g = interception efficiency of the inlet grate

E_g = $R_f E_o + R_s (1 - E_o)$ (Equation 8)

E_g = $(1.0)(0.61) + 0.15(1 - 0.61) = 0.67$ = 67 percent

Step B.16- Solve for (Q_{ig}):

Q_{ig} = interception flow of grate inlet

Q_{ig} = $E_g Q_t = 0.67(1.13) = 0.76$ cubic feet per second

Step B.17- Solve for (Q_i):

Q_i = total interception flow (both grate inlet and curb-opening extension)

Q_i = interception flow of curb-opening extension + interception flow of grate inlet

Q_i = $Q_{iex} + Q_{ig}$

Q_i = $0.78 + 0.76 = 1.54$ cubic feet per second

Step B.18- Solve for (Q_b):

Q_b = total bypass flow of upstream inlet (both grate inlet and curb-opening extension)

Q_b = $Q_{50} - Q_i$

Q_b = $1.90 - 1.54 = 0.36$ cubic feet per second

Step B.19- Calculate (L_2):

L_2 = distance between sag inlet CB-3 and CB-2, and

= distance between sag inlet CB-3 and CB-4

$$L_2 = \frac{43{,}560Q}{CC_f iW_p}E \quad \text{(Equation 1)}$$

Equation 1 is modified to calculate L_2 in sags, therefore

$$L_2 = \frac{43{,}560\,(Q_i - 2Q_b)}{C\ C_f\ i\ 2W_p}$$

i = 3.0 inches per hour (assume 5-minute t_c using a 50-year storm design, Hydrologic Zone 8, using IDR curve in **Chapter 7**)

C_f = 1.0

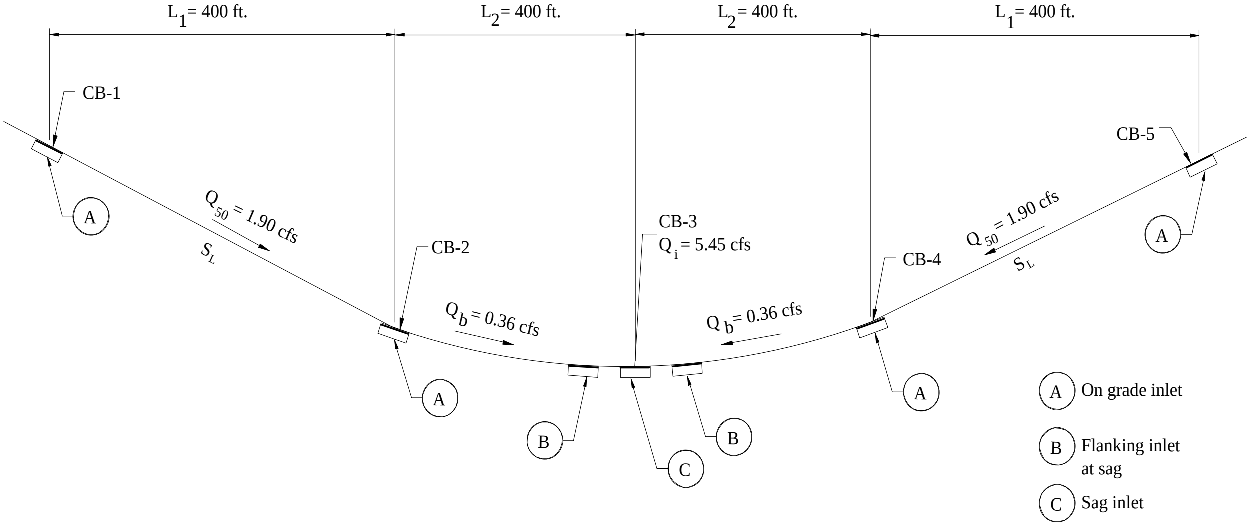
W_p = 75.5 feet

Q_i = 5.45 cubic feet per second (low point inlet (CB-3) interception capacity)

$$L_2 \quad = \quad \frac{43{,}560\,(5.45 - 2(0.36))}{(0.9)(1.0)(3.0)(2)(75.5)} = 505 \text{ feet}$$

Maximum inlet spacing shall be limited to 400 feet

505 feet is greater than 400 feet, therefore inlet spacing shall be limited to 400 feet.



SWEEPER COMBINATION INLETS

NTS

6.5 Trench Drain Systems (Sag)

The use of trench drains in sags is generally discouraged because of the tendency of such inlets to intercept debris and clog. However, there may be locations where it is desirable to supplement an existing low point inlet with the use of a trench drain.

Note: General information on trench drain systems is noted in Appendix C.

To aid in the design of trench drains, the designer should consider the following guidelines:

- Equations and figures used for the design of grate inlets (reference Section 6.1) should be used in the design of trench drains.
- Consider trench inlet hydraulic conveyance capacity curves or data from a manufacturer.
- Consider trench inlet hydraulic capacity curves or data for available grates from a manufacturer.
- Trench drain grate shall be a bicycle safe grate and is rated for heavy highway traffic.
- When using design Method B, the designer should assume 50 percent clogging which will result in providing twice the calculated required length for flow interception because trench drains tend to plug.
- The minimum cleanout velocity for trench drain systems should be 3 feet per second.

- Trench drains should not be used in areas with high traffic speeds greater than or equal to 45 miles per hour.

6.6 Flanking Inlets

Inlets should always be located at the low points of sag vertical curves. In addition to providing low point inlets, it is good engineering practice to place flanking inlets on each side of low point inlets when in a depressed area that stormwater has no outlet except through the drainage system. This is illustrated in Figure 6.

The purpose of flanking inlets is to act in relief of the inlet at the low point if it should become clogged or if the design spread is exceeded as noted in Table A. Flanking inlets can be located so they will function before water spread exceeds the allowable spread at the sump location. Also flanking inlets should be located so that they will receive all of the flow when the primary inlet at the bottom of the sag is clogged.

Note: When designing inlets in sag locations flanking inlets are neglected in the calculations.

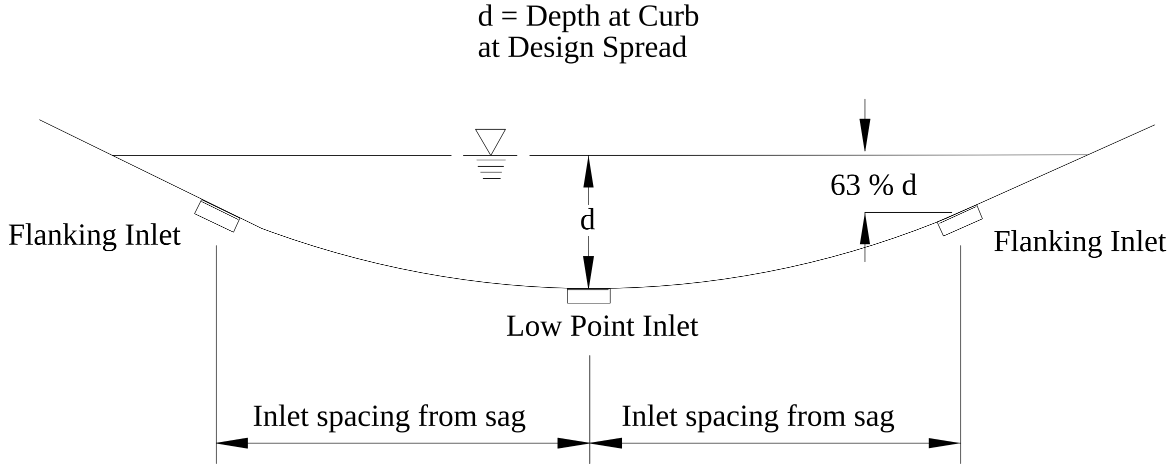


Figure 6 - Flanking Inlets

Flanking inlet design shall meet one of the following methods:

Method 1:
Flanking inlets should be placed 10-15 feet from the sag inlet and should be no more than 0.1 foot higher than the sag inlet. If this criteria does not fit the site conditions, determine the locations of the flanking inlets as described in Method 2.

Method 2:

Flanking inlets can be located so they will function before water spread exceeds the allowable spread at the sump location. The flanking inlets should be located so that they will receive all of the flow when the primary inlet at the bottom of the sag is clogged. They should do this without exceeding the allowable spread at the bottom of the sag. If the flanking inlets are the same dimension as the primary inlet, they will each intercept one-half the design flow when they are located so that the depth of ponding at the flanking inlets is 63 percent of the depth of ponding at the low point. If the flanking inlets are not the same size as the primary inlet, it will be necessary to either develop a new factor or do a trial and error solution using assumed depths with the weir equation to determine the capacity of the flanking inlet at the given depths.

Table D shows the spacing required for various depths at curb criteria and vertical curve lengths defined by:

$$K = \frac{L}{G_2 - G_1}$$

(Equation 22)

Where:

K = rate of vertical curvature

L = length of the vertical curve in feet

G_1 = beginning approach grade

G_2 = ending approach grade

Table D - Flanking Inlet Locations

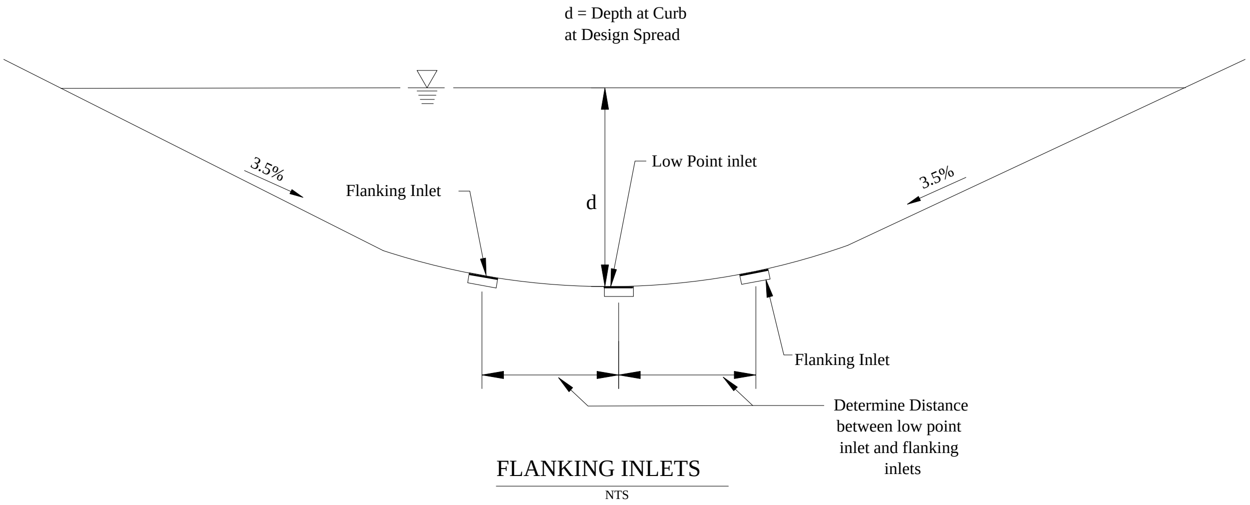
Distance to flanking inlets in sag vertical curve using depth at curb criteria (feet).										
K → (feet per percent) ↓ (feet) d	20	30	40	50	70	90	110	130	160	167
0.1	20	24	28	32	37	42	47	51	57	58
0.2	28	35	40	45	53	60	66	72	80	82
0.3	35	42	49	55	65	73	81	88	98	100
0.4	40	49	57	63	75	85	94	102	113	116
0.5	45	55	63	71	84	95	105	114	126	129
0.6	49	60	69	77	92	104	115	125	139	142
0.7	53	65	75	84	99	112	124	135	150	153
0.8	57	69	80	89	106	120	133	144	160	163
NOTES	1. $X = (200dK)^{0.5}$, where X = distance from the sag point (feet). 2. $d = Y - Y_f$ where Y = depth of ponding and Y_f = depth at the flanker inlet. 3. Drainage maximum K = 167 feet per percent.									

6.6.1 Flanking Inlets Example

The following example illustrates the procedure presented for Method 2.

6.6.1.1 Determine the location of the flanking inlets if located to function in relief of the inlet at the low point when the inlet at the low point is clogged

Sketch:



Given:

- Highway on-grade section, main line sag (45 miles per hour or greater)
- The spread at design flow (Q) is is not to exceed the shoulder width of 10 feet (per Table A).
- W_p = 46.5 feet (width of contributing drainage area, 4-12-foot lanes with 10-foot shoulder, 5-foot sidewalk, 7-foot median)
- L = 500 feet (vertical curve length at sag)
- S_x = 0.02 foot per foot (shoulder and lane cross section)
- G_1 = -3.5 percent (roadway slope entering sag)
- G_2 = 3.5 percent (roadway slope exiting sag)

Criteria:

- Flanking inlets should be designed so that they will receive all of the flow when the primary inlet at the bottom of the sag is clogged.
- Ponding at the flanking inlet should be 63 percent of the depth of ponding at the low point (for inlets of the same size)
- T = shoulder width + 0 feet = 10 feet (allowable total spread at inlet opening, per Table A, Appendix D)

Solution:

Step B.1- Solve for (K):

K = rate of vertical curvature

$$K = \frac{L}{(G_2 - G_1)} \qquad \text{(Equation 22)}$$

L = 500 feet (vertical curve length)

$$K = \frac{500}{\left[3.5 - (-3.5)\right]}$$

K = 71.4 feet per percent

Step B.2- Solve for (Y):

Y = depth of ponding at design spread.

$Y = S_x T$

$= (0.02)(10)$

Y = 0.20 feet

Step B.3- Solve for (Y_f):

Y_f = depth at flanker locations

Flanker inlet should be located so that depth at flanker is 63 percent of the depth at the sag inlet

$Y_f = 0.20(0.63) = 0.126$ feet

Step B.4- Solve for (X):

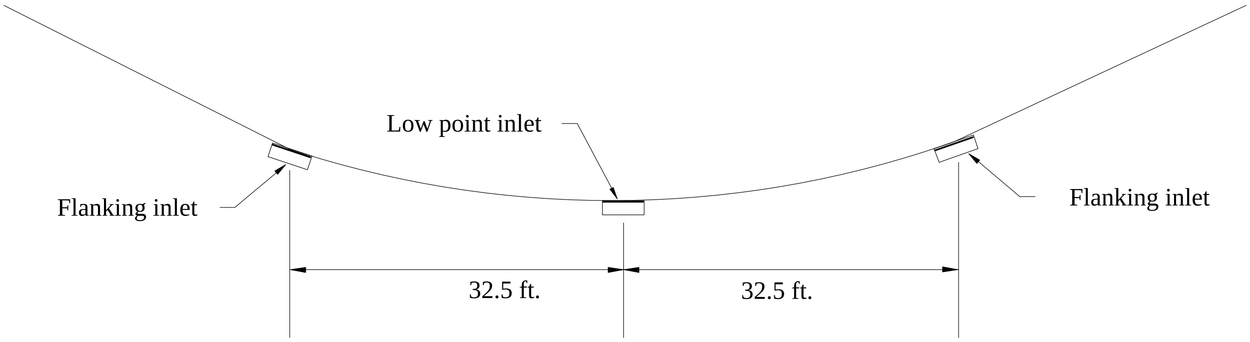
X = distance from flanker inlet to sag inlet

$X = (200dK)^{0.5}$

$d = Y - Y_f = 0.20 - 0.126 = 0.074$

$X = [(200)(0.074)(71.4)]^{0.5} = 32.5$ feet

Therefore, space flanking inlets at a distance no more than 32.5 feet from sag point.



FLANKING INLETS

NTS

Example problems in Section 6.0 illustrate the total interception capacity of inlets in sag locations. Except where inlets become clogged, spread on low gradient approaches to the low point is a more stringent criterion for design than the interception capacity of the sag inlet. It is recommended that a gradient of 0.3 percent be maintained within 50 feet of the level point in order to provide adequate drainage. Standard inlet locations may need to be adjusted to avoid excessive spread in the sag curve. Inlets may also be needed between the flankers and the ends of the curves. For major sag points, the flanking inlets are added as a safety factor, and are not considered as intercepting flow to reduce the bypass flow to the sag point. They are installed to assist the sag point inlet in the event of clogging.

7.0 Median Inlets

Standard ODOT drop inlets G-2M and G-2MA are recommended median and roadside ditch inlets as noted in Appendix C. These inlets are intended for portions of highways that have a very long continuous grade. When these inlets are placed in the clear zone the designer should evaluate that the proposed inlet location would not cause an errant vehicle to overturn.

The design examples in this section demonstrate the use of Chart 1, Chart 4, Chart 12, and Chart 13 located in Appendix H. These figures should be used in analyzing drop inlets in medians or roadside ditches on continuous grade. Charts 1 and 4 are used to estimate the ratios of frontal and side flow intercepted by the grate to total flow. The interception capacity of drop inlets in median ditches on continuous grades can be estimated by use of Charts 12 and 13 to estimate the flow depth and the ratio of frontal flow to total flow in the ditch.

Small dikes downstream of drop inlets (Figure 7) can be provided to impede bypass flow in an attempt to cause complete interception of the approach flow. The dikes usually need not be more than a few inches high and should have traffic safe slopes. The height of dike required for complete interception on continuous grades or the depth of ponding in sag vertical curves can be computed by use of Chart 8. The effective perimeter of a grate in an open channel with a dike should be taken as 2(L + W) since one side of the grate is not adjacent to a curb.

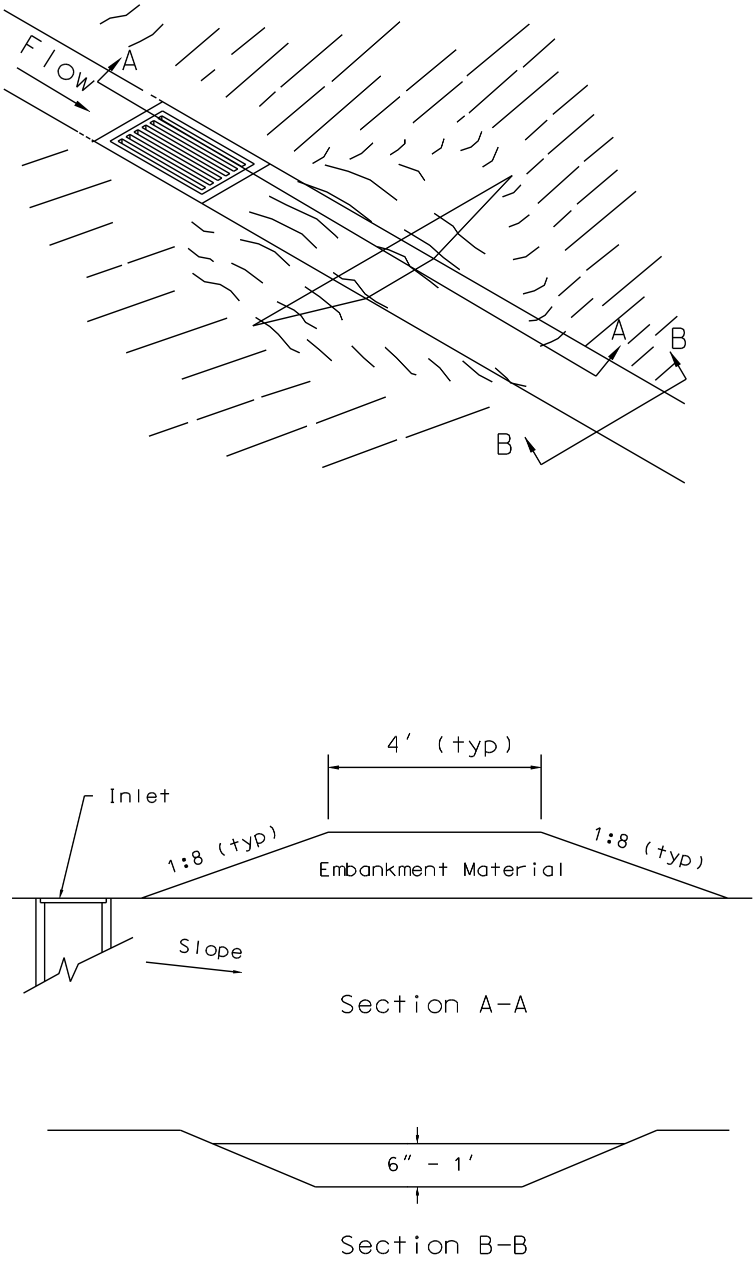


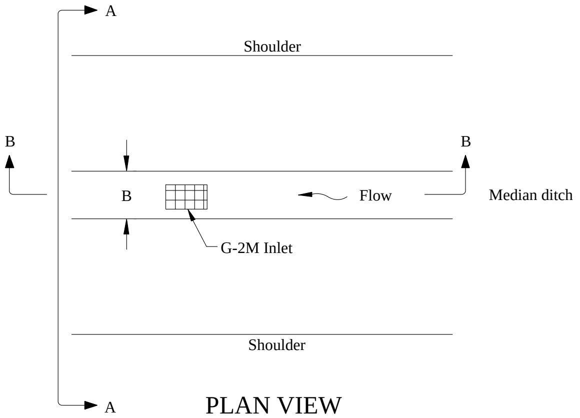
Figure 7 – Median Drop Inlet

7.1 Median Drop Inlet (On-grade) Example

The following example illustrates the design of a median drop inlet (on grade) with a grate width less than the bottom width of the ditch.

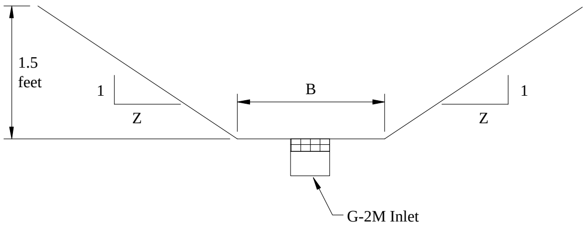
7.1.1 Determine the maximum allowable flow, interception flow, and bypass flow.

Sketch:



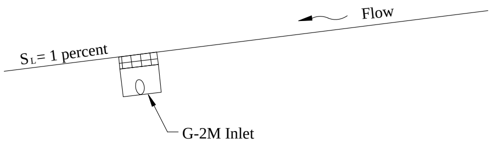
PLAN VIEW

NTS



SECTION A-A

NTS



SECTION B-B

NTS

Given:

- Urban collector, less than 45 miles per hour, on grade section
- S_L = 0.01 foot per foot (longitudinal slope of roadway and channel)
- W_p = 58 feet (width of contributing area, 2-12 foot travel lanes, 2-6 foot shoulders, 1-22 foot wide median)
- W_g = 2.25 feet (G-2M inlet grate width)
- L_g = 2.67 feet (G-2M inlet grate length)
- P_g = 9.83 feet (G-2M inlet grate perimeter)
- i = 2.28 inches per hour (10-year design, Hydrologic Zone 8 (IDR curves are located in **Chapter 7**))
- C = 0.42 (weighted rational method runoff coefficient for pavement and grass cover)
- B = 4 feet (channel bottom width)
- n = 0.073 (Manning’s coefficient for grass lined channel, reference **Chapter 8**)
- z = 6 feet (side slope, horizontal run per one foot of height)

- $D_{channel}$ = 1.5 feet (total channel depth)
- A = 1.01 Acres (total contributing area to median inlet)

7.1.2 Method A

Criteria:

- E = 0.70 (minimum efficiency for Method A)
- y_{max} = 0.5 feet (maximum flow depth to maintain minimum of 1 foot freeboard in ditch)

Solution:

Step A.1- Solve for (Q):

Q = peak runoff rate to inlet during 10-year event

Q = CiA **(Chapter 7)**

= (0.42)(2.28)(1.01)

= 0.96 cubic feet per second

Step A.2- Solve for (y):

Y = flow depth in channel during 10-year event

Use Manning's equation

$$Q = \left(\frac{1.486}{n}\right)R^{2/3}AS_L^{1/2}$$ **(Chapter 8)**

Solve for flow depth by trial and error by assuming a flow depth until Q equals 0.96 cubic feet per second.

y = 0.25 feet

Okay (because 0.25 feet is less than maximum allowable depth of 0.5 feet)

Step A.3- Solve for (P):

P = wetted perimeter in feet

$$P = B + 2y\sqrt{Z^2 + 1}$$ **(Chapter 8)**

y = 0.25 feet

$$P = 4 + 2(0.25)\sqrt{6^2 + 1} = 7.04 \text{ feet}$$

Step A.4- Solve for (A):

A = flow area in square feet.

A = $By + Zy^2$ **(Chapter 8)**
= $(4)(0.25) + (6)(0.25)^2$
= 1.38 square feet

Step A.5- Solve for (R):

R = hydraulic radius, feet

R = A/P
= 1.38 / 7.04
= 0.196 feet

Step A.6- Solve for (Q):

Q = flow rate in channel at assumed flow depth of 0.25 feet

$$Q = \left(\frac{1.486}{n}\right)R^{2/3}AS^{1/2}$$ (**Chapter 8**)

$$Q = \left(\frac{1.486}{0.073}\right)(0.196)^{2/3}(1.38)(0.01)^{1/2} = 0.96 \text{ cubic feet per second}$$

The flow calculated in this step is the same as that calculated in Step A.1. Therefore this flow depth of 0.25 feet is correct.

Step A.7- Solve for (V):

V = average flow velocity in channel at flow depth of 0.25 feet

V = Q / A (**Chapter 8**)

$$V = \left(\frac{Q}{A}\right) = \frac{0.96}{1.38} = 0.70 \text{ feet per second}$$

Note: To assure the channel is stable, the designer must evaluate that the maximum shear stress caused by the design flow is less than the maximum shear stress the lining can resist. The designer is directed to Chapter 8 for additional information.

Step A.8- Solve for (R_f):

R_f = ratio of frontal flow intercepted to total frontal flow

G-2M inlet equivalent grate type = P-1-$^7/_8$ (Table B, Appendix C)

L_g = 2.67 feet (G-2M grate length)

V_o = 9.7 feet per second (Chart 1, Appendix H)

$R_f = 1 – 0.09 (V – V_o)$ (Equation 6)

$R_f = 1 – 0.09 (0.70– 9.7) = 1.81$

R_f cannot be greater than 1, therefore $R_f = 1.0$

Step A.9- Solve for (R_s):

R_s = ratio of side flow intercepted to total side flow

$$R_s = R_s = \frac{1}{1+\left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)} \qquad \text{(Equation 7)}$$

$$R_s = \frac{1}{1+\left(\frac{0.15(0.70)^{1.8}}{(0.01)(2.67)^{2.3}}\right)} = 0.55$$

Note: S_x is assumed to be 1 percent because the ditch bottom is wider than the grate and has no cross-slope, therefore, per FHWA HEC-22 recommends using the least cross-slope (1 percent) noted in Chart 4, Appendix H.

Step A.10- Solve for (E_o):

E_o = ratio of frontal flow to total flow in trapezoidal channel

$$E_o = \frac{W_g}{B+yZ} \qquad \text{(Chart 13, Appendix H)}$$

W_g = 2.25 feet (G-2M grate width) (Table B, Appendix C)

$$E_o = \frac{2.25}{[4+0.25(6)]} = 0.41$$

Step A.11- Solve for (E):

E = inlet efficiency

E = $R_f E_o + R_s (1 – E_o)$ (Equation 8)

E = 1 (0.41) + 0.55(1 – 0.41) = 0.73

E = 0.73 is greater than the minimum allowable interception efficiency, therefore criteria of minimum efficiency is met.

Step A.12- Solve for (Q_i):

Q_i = intercepted flow in cubic feet per second

Q_i = EQ_t

Q_i = (0.73) (0.96) = 0.70 cubic feet per second

Step A.13- Solve for (Q_b):

Q_b = flow that is not intercepted by the inlet and must be included in the evaluation of downstream channels and inlets

Q_b = Q_t - Q_i

Q_b = 0.96 – 0.70 = 0.26 cubic feet per second

7.1.3 Method B

Criteria:

- Assume 30 percent clogging of a type G-2M grate (per Table A)
- L_g = 2.26 feet (G-2M grate length, 30 percent clogged)
- W_g = 1.84 feet (G-2M grate width, 30 percent clogged)
- y_{max} = 0.5 feet (maximum flow depth to maintain minimum of 1 foot freeboard in ditch)

Solution:

Step B.1- Solve for (Q):

Q = peak runoff rate to inlet during 10-year event

Q = CiA (**Chapter 7**)

= (0.42)(2.28)(1.01)

= 0.96 cubic feet per second

Step B.2- Solve for (y):

y = flow depth in channel during 10-year event

Use Manning’s equation

$$Q = \left(\frac{1.486}{n}\right)R^{2/3}AS_L^{1/2}$$ (**Chapter 8**)

Solve for flow depth by trial and error by assuming a flow depth until Q equals 0.96 cubic feet per second.

y = 0.25 feet

Okay (because 0.25 feet is less than maximum allowable depth of 0.5 feet)

Step B.3- Solve for (P):

P = wetted perimeter in feet

$$P = B + 2y\sqrt{Z^2 + 1}$$ (**Chapter 8**)

y = 0.25 feet

$$P = 4 + 2(0.25)\sqrt{6^2 + 1} = 7.04 \text{ feet}$$

Step B.4- Solve for (A):

A = flow area in square feet.

$A = By + Zy^2$ (**Chapter 8**)

$= (4)(0.\ 25) + (6)(0.25)^2$

= 1.38 square feet

Step B.5- Solve for (R):

R = hydraulic radius, feet

R = A/P
= 1.38/7.04
= 0.196 feet

Step B.6- Solve for (Q):

Q = flow rate in channel at assumed flow depth of 0.25 feet

$$Q = \left(\frac{1.486}{n}\right) R^{2/3} A S^{1/2}$$ (**Chapter 8**)

$$Q = \left(\frac{1.486}{0.073}\right)(0.196)^{2/3}(1.38)(0.01)^{1/2} = 0.96 \text{ cubic feet per second}$$

The flow calculated in this step is the same as that calculated in Step B.1. Therefore this flow depth of 0.25 feet is correct.

Step B.7- Solve for (V):

V = average flow velocity in channel at flow depth of 0.25 feet

V = Q / A (**Chapter 8**)

$$V = \left(\frac{Q}{A}\right) = \frac{0.96}{1.38} = 0.70 \text{ feet per second}$$

Note: To assure the channel is stable, the designer must evaluate that the maximum shear stress caused by the design flow is less than the maximum shear stress the lining can resist. The designer is directed to ***Chapter 8*** *for additional information.*

Step B.8- Solve for (R_f):

R_f = ratio of frontal flow intercepted to total frontal flow

G-2M inlet equivalent grate type = P-1-$^7/_8$ (Table B, Appendix C)

L_g = 2.26 feet (G-2M grate length, 30 percent clogged)

V_o = 8.6 feet per second (Chart 1, Appendix H)

R_f = $1 – 0.09 (V – V_o)$ (Equation 6)

R_f = 1 – 0.09 (0.70– 8.6) = 1.71

R_f cannot be greater than 1, therefore R_f = 1.0

Step B.9- Solve for (R_s):

R_s = ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\frac{0.15V^{1.8}}{S_x L^{2.3}}\right)} \qquad \text{(Equation 7)}$$

$$R_s = \frac{1}{1+\left(\frac{0.15(0.70)^{1.8}}{(0.01)(2.26)^{2.3}}\right)} = 0.45$$

Step B.10- Solve for (E_o):

E_o = ratio of frontal flow to total flow in trapezoidal channel

$$E_o = \frac{W_g}{B + yZ} \qquad \text{(Chart 13, Appendix H)}$$

W_g = 1.84 feet (G-2M grate width, 30 percent clogged) (Table B, Appendix C)

$$E_o = \frac{1.84}{(4 + 0.25(6))} = 0.34$$

Step B.11- Solve for (E):

E = inlet efficiency

$E = R_f E_o + R_s (1 – E_o)$ (Equation 8)

E = 1(0.34) + 0.45(1 – 0.34) = 0.64

Okay because 70 percent interception criteria is not required for Method B.

Step B.12- Solve for (Q_i):

Q_i = intercepted flow in cubic feet per second

Q_i = EQ_t

Q_i = (0.64) (0.96)

Q_i = 0.61 cubic feet per second

Step B.13- Solve for (Q_b):

Q_b = flow that is not intercepted by the inlet and must be included in the evaluation of downstream channels and inlets

Q_b = Q_t - Q_i

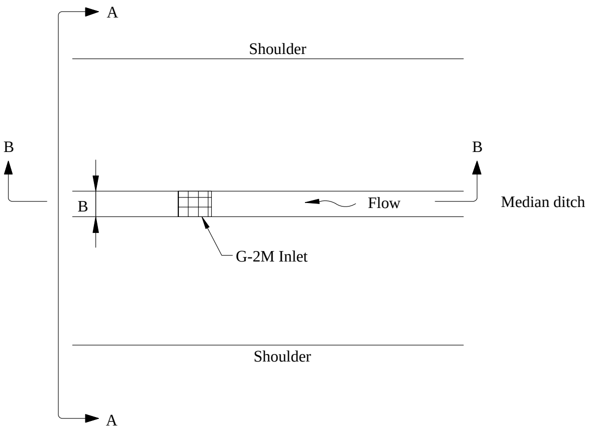
Q_b = 0.96 – 0.61 = 0.35 cubic feet per second

7.2 Median Drop Inlet (On-grade) Example

The following example illustrates the use of Chart 4 (Appendix H) when the grate width is equal to the bottom width of the ditch. Use Chart 4 by substituting ditch side slopes for values of S_x as illustrated in the following example:

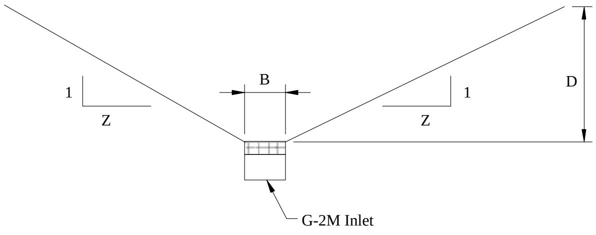
7.2.1 Determine the intercepted flow (Q_i) and the bypassed flow (Q_b) for the following conditions.

Sketch:



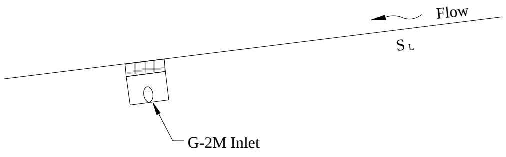
PLAN VIEW

NTS



SECTION A-A

NTS



SECTION B-B

NTS

Given:

Note: Method A or Method B could be used. Method selected should be used for entire design.

- Q = 20.0 cubic feet per second (10-year peak runoff)
- Urban collector, greater than 45 milers per hour, on-grade section
- B = 2.25 feet (channel width)
- n = 0.027 (Manning's roughness coefficient)
- z = 6 (channel side slope)
- S_L = 0.0125 feet per feet (longitudinal slope of channel and roadway)
- D = 2.0 feet (total ditch depth)
- The flow in the median ditch is to be intercepted by a drop inlet
- Type G-2M inlet with a P-1-$^{7}/_{8}$ parallel bar grate
- W_g = 2.25 feet (grate width for G-2M inlet)
- L_g = 2.67 (grate length for G-2M inlet)
- There is no dike downstream of the inlet.

7.2.2 Method A

Solution:

Step A.1- Solve for (y):

y = flow depth in channel during a 10-year event.

Use Manning's equation

$$Q = \left(\frac{1.486}{n}\right) R^{2/3} A S_L^{1/2}$$ (**Chapter 8**)

Solve for flow depth by trial and error. Start by assuming a flow depth.

y = 0.78 feet

Step A.2- Solve for (P):

P = wetted perimeter, feet

$$P = B + 2y\sqrt{Z^2 + 1}$$ (**Chapter 8**)

y = 0.78 feet

$$P = 2.25 + 2(0.78)\sqrt{6^2 + 1} = 11.74 \text{ feet}$$

Step A.3- Solve for (A):

A = flow area, square feet.

$A = By + Zy^2$ (**Chapter 8**)

$= (2.25)(0.78) + (6)(0.78)^2$

= 5.41 square feet

Step A.4- Solve for (R):

R = hydraulic radius, feet

R = A/P = 5.41/11.74 = 0.46 feet

Step A.5- Solve for (Q):

Q = flow rate in channel at assumed flow depth of 0.78 feet

$$Q = \left(\frac{1.486}{n}\right) R^{2/3} A S^{1/2}$$ (**Chapter 8**)

$$Q = \left(\frac{1.486}{0.027}\right)(0.46)^{2/3}(5.41)(0.0125)^{1/2} = 20.0 \text{ cubic feet per second}$$

The flow calculated in this step is the same as that given in the problem statement. Therefore this flow depth is correct.

Step A.6- Solve for (V):

V = average flow velocity in channel at flow depth of 0.78 feet

V = Q/A (**Chapter 8**)

= 20.0/5.41 = 3.70 feet per second

Step A.7- Solve for (R_f):

R_f = ratio of frontal flow intercepted to total frontal flow

G-2M inlet equivalent grate type = P-1-$^7/_8$ parrallel pipe. (Table B, Appendix C)

L_g = 2.67 feet (G-2M grate length)

V_o = 9.7 feet per second (Chart 1, Appendix H)

$R_f = 1 – 0.09\ (V – V_o)$ (Equation 6)

$R_f = 1 – 0.09\ (3.70– 9.7) = 1.54$

R_f cannot be greater than 1, therefore R_f = 1.0

Step A.8- Solve for (R_s):

R_s = ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\dfrac{0.15(V)^{1.8}}{S_x(L)^{2.3}}\right)}$$ (Equation 7, or Chart 4, Appendix H)

$$R_s = \frac{1}{1+\left(\dfrac{0.15(3.70)^{1.8}}{0.17(2.67)^{2.3}}\right)} = 0.51$$

Note: $S_x = \dfrac{1}{Z}$ *per FHWA HEC-22*

Step A.9- Solve for (E_o)

E_o = ratio of frontal flow to total flow in trapezoidal channel

$$E_o = \frac{W_g}{B + yZ}$$ (Chart 13, Appendix H)

W_g = 2.25 feet (G-2M grate width) (Table B, Appendix C)

$$E_o = \frac{2.25}{(2.25 + 0.78(6.0))} = 0.32$$

Step A.10- Solve for (E):

E = total efficiency.

$E = E_o R_f + R_s (1 - E_o)$ (Equation 8)

$E = (0.32)(1.0) + (0.51)(1-0.32) = 0.67$

The minimum allowable inlet efficiency when using Method A is 70 percent. Therefore the design would have to be modified to meet efficiency requirements such as adding an additional inlet upstream to reduce peak flow to this inlet or use Method B or by constructing a barrier downstream of the inlet to force the water into the inlet. This method is demonstrated in example problem 7.3.

7.2.3 Method B

Criteria:

- Assume 30 percent clogged type G-2M inlet with a P-1-$^7/_8$ parallel bar grate
- W_g = 1.84 feet (grate width for G-2M inlet, per Table B)
- L_g = 2.26 (grate length for G-2M inlet, per Table B)

Solution:

Step B.1- Solve for (y):

y = flow depth in channel during a 10-year event.

Use Manning's equation

$$Q = \left(\frac{1.486}{n}\right) R^{2/3} A S_L^{1/2}$$ (**Chapter 8**)

Q = 20 cubic feet per second

Solve for flow depth by trial and error. Start by assuming a flow depth.

y = 0.78 feet

Step B.2- Solve for (P):

P = wetted perimeter, feet

$$P = B + 2y\sqrt{Z^2 + 1}$$ (**Chapter 8**)

y = 0.78 feet

$$P = 2.25 + 2(0.78)\sqrt{6^2 + 1} = 11.74 \text{ feet}$$

Step B.3- Solve for (A):

A = flow area, square feet.

$A = By + Zy^2$ (**Chapter 8**)

$= (2.25)(0.78) + (6)(0.78)^2$

$= 5.41$ square feet

Step B.4- Solve for (R):

R = hydraulic radius, feet

$R = A/P = 5.41/11.74 = 0.46$ feet

Step B.5- Solve for (Q):

Q = flow rate in channel at assumed flow depth of 0.78 feet

$$Q = \left(\frac{1.486}{n}\right) R^{2/3} A S^{1/2}$$ (**Chapter 8**)

$$Q = \left(\frac{1.486}{0.027}\right)(0.46)^{2/3}(5.41)(0.0125)^{1/2} = 20.0 \text{ cubic feet per second}$$

The flow calculated in this step is the same as that given in the problem statement. Therefore this flow depth is correct.

Step B.6- Solve for (V):

V = average flow velocity in channel at flow depth of 0.78 feet

$V = Q/A$ (**Chapter 8**)

$= 20.0/5.41 = 3.70$ feet per second

Step B.7- Solve for (R_f):

R_f = ratio of frontal flow intercepted to total frontal flow

G-2M inlet equivalent grate type = P-1-$^{7}/_{8}$ parrallel pipe. (Table B, Appendix C)

L_g = 2.26 feet (G-2M grate length 30 percent clogged, Table B)

V_o = 8.6 feet per second (Chart 1, Appendix H)

$R_f = 1 – 0.09\ (V – V_o)$ (Equation 6)

$R_f = 1 – 0.09\ (3.70 – 8.6) = 1.44$

R_f cannot be greater than 1, therefore $R_f = 1.0$

Step B.8- Solve for (R_s):

R_s = ratio of side flow intercepted to total side flow

$$R_s = \frac{1}{1+\left(\frac{0.15(V)^{1.8}}{S_x(L)^{2.3}}\right)} \qquad \text{(Equation 7)}$$

$$R_s = \frac{1}{1+\left(\frac{0.15(3.70)^{1.8}}{0.17(2.26)^{2.3}}\right)} = 0.41$$

Step B.9- Solve for (E_o)

E_o = ratio of frontal flow to total flow in trapezoidal channel

$$E_o = \frac{W}{B + yZ} \qquad \text{(Chart 13, Appendix H)}$$

W_g = 1.84 feet (G-2M grate width, 30 percent clogged, Table B)

$$E_o = \frac{1.84}{(2.25 + 0.78(6.0))} = 0.27$$

Step B.10- Solve for (E):

E = total efficiency.

$E = E_o R_f + R_s (1 - E_o)$ (Equation 8)

E = (0.27)(1.0) + (0.41)(1-0.27) = 0.57

Step B.11- Solve for (Q_i, Q_b):

Q_i = interception flow in cubic feet per second

Q_b = flow that is not intercepted by the inlet and must be included in the evaluation of downstream channels and inlets

Q_i = EQ = (0.57)(20.0)

Q_i = 11.4 cubic feet per second

Q_b = $Q – Q_i$ = 20.0 – 11.4

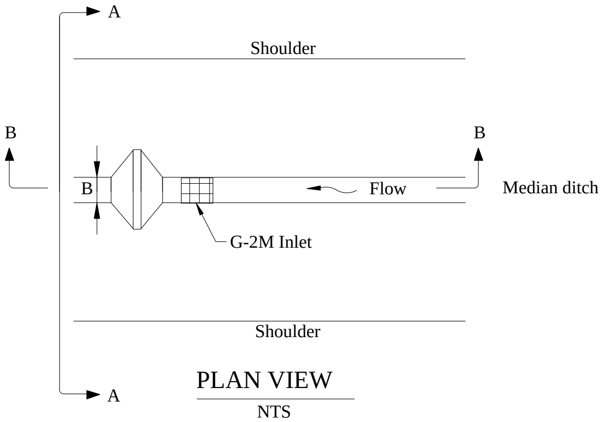
Q_b = 8.6 cubic feet per second

7.3 Median Drop Inlet (On-grade) Example

7.3.1 Determine the dike height required downstream of the grate inlet to provide total interception of ditch flow

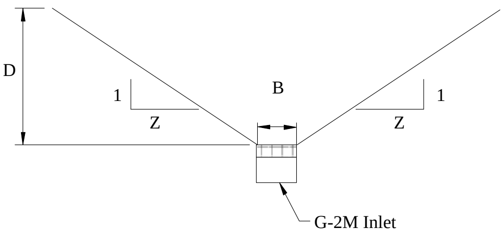
The following example uses the conditions provided in Example 7.2.1 to illustrate the procedure of designing a dike downstream of a drop inlet that would provide adequate obstruction to cause total interception of ditch flow.

Sketch:



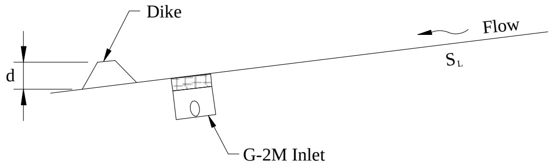
PLAN VIEW

NTS



SECTION A-A

NTS



SECTION B-B

NTS

Given:

- Q = 20 cubic feet per second (10-year peak runoff)
- B = 2.25 feet (channel width)
- L_g = 2.67 feet (type G-2M inlet length)
- W_g = 2.25 feet (type G-2M inlet width)
- n = 0.027 (Manning's roughness coefficient)
- z = 6 (channel side slope)
- S_L = 0.0125 feet per feet (longitudinal slope of channel and roadway)
- The flow in the median ditch is to be intercepted by a drop inlet (type G-2M measuring 2.25 feet by 2.67 feet with a P-1-$^7/_8$ parallel bar grate).

Solution:

Step 1- Solve for (P_g):

P_g = grate perimeter

P_g = $2(L_g+W_g)$

P_g = $2(2.67 + 2.25) = 9.84$ feet

Step 2- Solve for (d):

d = depth of flow required for 100 percent interception

d = $[Q_i / (C_w\ P_g)]^{0.67}$ (Equation 13 or Chart 8, Appendix H)

For 100 percent interception, $Q_i = Q = 20$ cubic feet per second

C_w = 3.0

P_g = 9.84

d = $[(20) / ((3.0)(9.84))]^{0.67} = 0.77$ feet

An obstruction berm will need to have a minimum height of 0.77 feet for total interception.

8.0 Embankment Inlets/Downdrains

There will be locations where disposal of runoff must be provided at the drainage inlet. This is often the case along fill slopes or to intercept water upgrade or downgrade of bridges. The flow intercepted is usually discharged into open chutes or pipe downdrains that terminate at the toe of the fill slope.

Listed below are additional guidelines that need to be addressed when designing these inlets:

- Water quality treatment – runoff collected by these drainage inlets need to address the most stringent local standards or refer to ODOT's water quality design guidelines.
- Energy dissipation – the designer is referred to Chapter 11 to design outfalls meeting ODOT design guidelines.
- Conveyance capacity – the designer is referred to Appendix F for storm pipe design and this section for downdrain design guidelines.

Example problem solutions in other sections of this manual illustrate the difficulty in providing for near total interception on-grade. Grate inlets intercept little more than the flow conveyed by the gutter width occupied by the grate. Combination curb-opening and grate inlets can be designed to intercept total flow if the length of curb-opening upstream of the grate is sufficient to reduce spread in the gutter to the width of the grate used. Depressing the inlets or curb-opening would significantly reduce the length of inlet required. Therefore, the most practical procedure for use where near total interception is necessary are sweeper inlets, increased grate width, or slotted inlets of sufficient length.

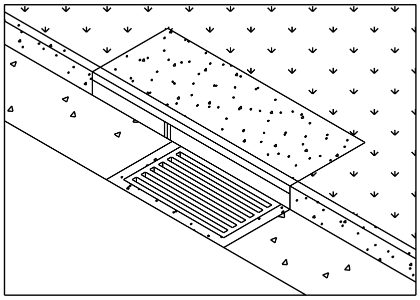
Note: Design charts and procedures in Section 5.0 are applicable to the design of inlets on embankments.

Drainage piping systems used to convey intercepted flow from inlets to the toe of a fill slope may be open or closed chutes.

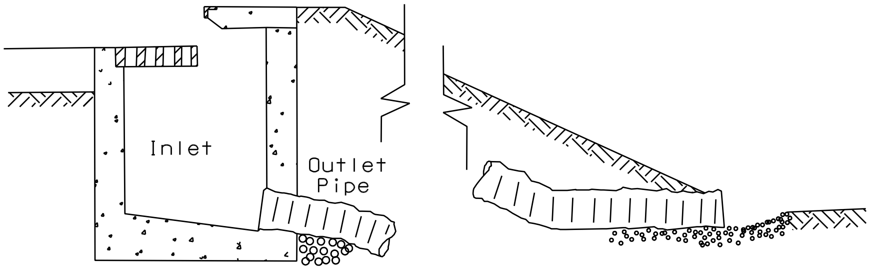
Pipe downdrains (closed chutes) are preferable because the flow is confined and cannot cause erosion along the sides. Open chutes are often damaged by erosion from water splashing over the sides of the chute due to oscillation in the flow and from spill over the sides at bends in the chute.

Note: It is recommended that these types of pipes be buried to minimize bank erosion and eliminate interference with maintenance operations.

Erosion at the ends of downdrains or chutes can be a problem if not anticipated. To control the potential for pipe outlet erosion the designer is referred to **Chapter 11** for information on energy dissipation guidelines.



a. Perspective



b. Section

Figure 8 - Embankment inlet and downdrain.

The capacity of downdrain pipes are most commonly restricted by inlet control as described in **Chapter 9**. Capacities are shown in Table E assuming the headwater depth does not exceed the diameter of the pipe (HW/D=1). Downdrain pipes controlled by pipe capacity can be sized using Manning's equation as described in **Chapter 8**.

Table E - Downdrain Pipe Capacity

Diameter of Slope Pipe (inches)	Maximum Design Flow (cubic feet per second)
12	2.0
15	3.7
18	5.7
21	8.1
24	11.8

9.0 Scuppers

Scuppers are another way of removing stormwater from roadway pavement and bridge decks. The primary advantage of using scuppers is their ability to intercept flow over a wide section and offer little interference to traffic operations. However, scuppers are not recommended for use in environments where significant sediment or debris loads may be present because they are susceptible to clogging.

Note: Reference Roadway Concrete Barrier section of ODOT's Standard Drawings (current version) for typical horizontal scuppers used in ODOT storm drainage systems. For a more detailed discussion of horizontal and vertical scuppers, the reader is referred to FHWA's "Design of Bridge Deck Drainage" - Hydraulic Engineering Circular No 21.

Listed below are additional guidelines that need to be addressed when designing scuppers:

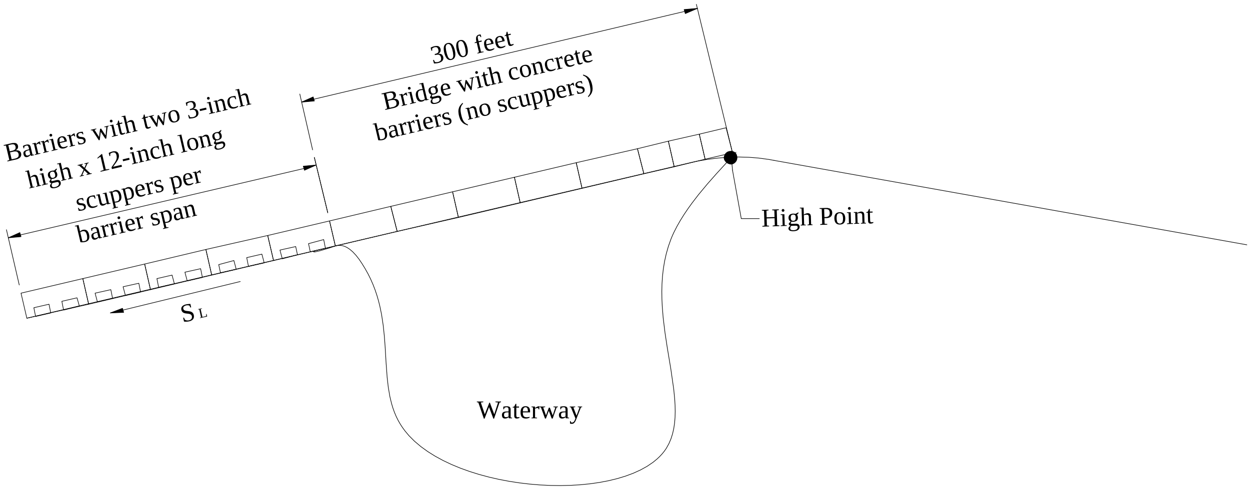
- The equations and figures used for the design of curb-opening inlets should be used in the design of horizontal scuppers.
- The equations and figures used for the design of grate inlets should be used in the design of vertical scuppers.
- Water quality treatment – runoff collected by scuppers needs to address the most stringent local standards or refer to ODOT's water quality design guidelines. Due to environmental regulations it is discouraged to directly discharge from bridge decks using scuppers onto waterways, riparian areas, wetlands, or other sensitive areas. It is good practice to assume all bridge deck runoff will have water quality treatment unless permit or environmental personnel give permission to do otherwise.
- When using inlet design method B, the designer should assume 50 percent clogging which will result in providing twice the calculated required length for flow interception because scuppers tend to plug.
- Energy dissipation – flow exiting horizontal scuppers should be closely evaluated for erosion potential because the flow is not directed to a storm drain system and is often released directly onto down slopes. Reference ODOT's Erosion Control Manual, **Chapter 8,** and **Chapter 11** for recommended methods to prevent erosion.

9.1 Scupper (On-grade) Example

The following example illustrates the design of horizontal scuppers.

9.1.1 Determine inlet efficiency of concrete barrier scuppers

Sketch:



SCUPPERS

NTS

Given:

- Highway section on-grade (greater than 45 miles per hour)
- L_b = 5.5 feet (length of barrier between scuppers)
- W_P = 31 feet (width of contributing area, 2 – 12-foot lanes with 7-foot shoulder)
- S_L = 0.01 feet per feet
- S_X = 0.02 feet per feet
- n = 0.016 (Manning’s coefficient for asphalt placement)
- 10-year design (per Table A), Salem area (Hydrologic Zone 7)
- i = 2.10 inches per hour (Salem area, assume 5-minute t_c using a 10-year storm design)
- Type A curb and gutter (reference Chapter 8)

9.1.2 Method A

Criteria:

- T = allowable spread = shoulder width + 0 feet = 7 feet (per Table A)
- L_S = scupper length = (1 foot)
- h_S = 3 inches (scupper height)

Solution:

Step A.1- Solve for (Q):

Q = flow rate to first upstream scupper in cubic feet per second

Q = CiA (**Chapter 7**)

A = (300)(31) = 9300 square feet = 0.21 acres

Q = (.90)(2.10)(0.21) = 0.40 cubic feet per second

Step A.2- Solve for (T):

T = total spread at upstream scupper (**Chapter 8**)

$$T = \left(\frac{Q_{10}n}{0.56(S_L)^{.5}(S_X)^{1.67}}\right)^{0.375}$$

$$T = \left(\frac{(0.40)(0.016)}{0.56(0.01)^{.5}(0.02)^{1.67}}\right)^{0.375} = 5.1 \text{ feet}$$

Spread at first upstream scupper = 5.1 feet

Allowable spread = 7 feet. Therefore, no deck drains will be needed between the high point and first upstream scupper because maximum spread is less than allowable spread.

Step A.3- Solve for (L_T):

L_T = length of opening to intercept 100 percent of the gutter flow in feet

$$L_T = 0.6Q^{0.42}\,S_L^{\,0.30}\left(\frac{1}{nS_x}\right)^{0.6} \quad \text{(Equation 10)}$$

$$L_T = 0.6(0.40)^{0.42}(0.01)^{0.30}\left(\frac{1}{(0.016)(0.02)}\right)^{0.6}$$

L_T = 13 feet

Step A.4- Solve for (E):

E = scupper-opening interception efficiency

$$E = 1-\left(1-\frac{L}{L_T}\right)^{1.8} \quad \text{(Equation 11)}$$

$$E = 1-\left(1-\frac{1.0}{13}\right)^{1.8} = 0.13$$

E = 13 percent

The minimum allowable inlet efficiency when using Method A is 70 percent. Therefore, the design would have to be modified to meet efficiency requirements such as adding additional inlets as necessary, using barriers with no scuppers and using inlets, or using Method B

9.1.3 Method B

Criteria:

- For scuppers use a 50 percent clogging factor (per Table A)
- T = allowable spread = shoulder width + 0 feet = 7 feet (per Table A)
- L_S = scupper length = (1 foot)(50 percent) = 0.5 feet
- h_S = 3 inches (scupper height)

Solution:

Step B.1- Solve for (Q):

Q = flowrate to first upstream scupper in cubic feet per second

Q = CiA (**Chapter 7**)

A = (300)(31) = 9300 square feet = 0.21 acres

Q = (.90)(2.10)(0.21) = 0.40 cubic feet per second

Step B.2- Solve for (T):

T = total spread at upstream scupper (**Chapter 8**)

$$T = \left(\frac{Q_{10}n}{0.56(S_L)^{.5}(S_X)^{1.67}}\right)^{0.375}$$

$$T = \left(\frac{(0.40)(0.016)}{0.56(0.01)^{.5}(0.02)^{1.67}}\right)^{0.375} = 5.1 \text{ feet}$$

Spread at first upstream scupper = 5.1 feet

Allowable spread = 7 feet. Therefore, no deck drains will be needed between the high point and first upstream scupper because maximum spread is less than allowable spread.

Step B.3- Solve for (L_T):

L_T = length of opening to intercept 100 percent of the gutter flow in feet

$$L_T = 0.6Q^{0.42}\,S_L^{\ 0.30}\left(\frac{1}{nS_x}\right)^{0.6} \qquad \text{(Equation 10)}$$

$$L_T = 0.6(0.40)^{0.42}(0.01)^{0.30}\left(\frac{1}{(0.016)(0.02)}\right)^{0.6}$$

L_T = 13 feet

Step B.4- Solve for (E):

E = scupper-opening interception efficiency

$$E = 1-\left(1-\frac{L}{L_T}\right)^{1.8} \quad \text{(Equation 11)}$$

$$E = 1-\left(1-\frac{0.5}{13}\right)^{1.8} = 0.068$$

E = 6.8 percent

Okay, 70 percent minimum efficiency criteria does not apply to Method B

Step B.5- Solve for (Q_i):

Q_i = intercepted flow by the first scupper

Q_i = EQ = (0.068)(0.40) = 0.0272 cubic feet per second

Step B.6- Solve for (Q_b):

Q_b = bypass flow from the first scupper

$Q_b = Q – Q_i$

Q_b = 0.40 – 0.0272 = 0.37 cubic feet per second

Step B.7- Solve for (Q):

Q = flow to second scupper in cubic feet per second

$Q = Q_b + Q_2$

Q_b = 0.37 cubic feet per second

Q_2 = CiA (**Chapter 7**)

L_b = 5.5 feet (length of barrier between scuppers)

A = L_bW = (31 feet)(5.5 feet) = 171 ft^2 = 0.004 acres

Q_2 = (0.90)(2.10)(0.004) = 0.008 cubic feet per second

Q = 0.37 + 0.008 = 0.378 cubic feet per second

Step B.8- Solve for (T):

T = flow spread at second scupper

$$T = \left(\frac{Qn}{0.56(S_L)^{0.5}(S_X)^{1.67}}\right)^{0.375} \qquad \textbf{(Chapter 8)}$$

$$T = \left(\frac{(0.378)(0.016)}{0.56(0.01)^{0.5}(0.02)^{1.67}}\right)^{0.375} = 5.0 \text{ feet}$$

Spread at second and subsequent scuppers is approximately 5.0 feet. Allowable spread is 7 feet; this is acceptable because maximum spread is less than allowable spread.